THE BIRTH AND DEATH OF THE SUN

Stellar Evolution and Subatomic Energy

Some say the world will end in fire;
Some say in ice. —ROBERT FROST

THE *Birth and Death of the* SUN

STELLAR EVOLUTION AND SUBATOMIC ENERGY

GEORGE GAMOW

PROFESSOR OF THEORETICAL PHYSICS, GEORGE WASHINGTON UNIVERSITY

ILLUSTRATED BY THE AUTHOR

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Dedicated to

PROFESSOR H. N. RUSSELL

Preface

HOW did our Sun come into being, what keeps it hot and luminous, and what will be its ultimate fate? These are questions that should be of interest to all the inhabitants of our globe, whose life and prosperity are entirely dependent upon the radiant energy coming from the Sun.

Since the beginning of scientific thought, the problem of solar energy sources has been one of the most exciting, but also one of the most difficult puzzles of nature. But only during the last decade has it become possible to tackle the problem of solar energy generation with any hope of a correct scientific solution, and thereby to answer questions concerning the past, present, and future of our Sun. It has finally been demonstrated that the tremendous amounts of energy radiated by the Sun are generated by the transformation of chemical elements taking place in its interior, precisely those "transmutations of elements," in fact, that had been so unsuccessfully pursued by medieval alchemists.

As our Sun represents only one member of the numerous family of stars scattered through the vast spaces of the universe, the answer to this solar problem necessarily involves also the question of the evolutionary history of stars, and this brings us back to the fundamental puzzle concerning the creation of the stellar universe.

In this book, the author, who has been closely connected

with the progress of research on these problems, attempts to give, in the simplest terms of which he is capable, an outline of the fundamental discoveries and theories that now permit us a general view of the evolution of our world. Many of the views touched on in this work have been so recently arrived at that they have never before been discussed in popular literature.

Though the author cannot conclude this preface with the customary statement that "all the characters appearing herein are purely imaginary and have no connexion with any living person," it is perhaps best that he warn the reader against giving too great credence to such minutiæ in the following pages as the untidiness of Democritus's beard, the rainy weather in Princeton at the time of the construction of the Russell diagram, and the relationship between Dr. Hans Bethe's famous appetite and his rapid solution of the problem of solar reaction.

The author considers it his pleasant duty to express his gratitude to his friend Dr. Desmond H. Kuper for reading the manuscript and for giving much valuable advice on the translation of ergs into calories and on other similar questions.

George Gamow

George Washington University
January 1, 1940

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Note on Units of Measurement

In this book the decimal metric system, universally accepted in scientific research, is used. For those readers who are more accustomed to feet, pounds, and the Fahrenheit temperature scale, we give the following table of equivalences:

1 centimetre	=	0.39 inch
1 kilometre	=	0.62 mile
1 gramme	=	0.035 ounce
1 kilogram	=	2.20 pounds

To convert into Fahrenheit the temperatures here given in Centigrade, multiply by $\frac{9}{5}$ and add 32 (e.g., 20° C. is the same as $20 \times \frac{9}{5} + 32 = 68°$ F.).

The Sun and Its Energy

THE SUN AND LIFE ON EARTH

"WHICH is more useful, the Sun or the Moon?" asks Kuzma Prutkov, the renowned Russian philosopher,* and after some reflection he answers himself: "The Moon is the more useful, since it gives us its light during the night, when it is dark, whereas the Sun shines only in the daytime, when it is light anyway."

Of course, every schoolboy knows that moonshine consists only of the reflected rays of the Sun, but it is still far from universally understood that there is scarcely a phenomenon on earth the origin of which cannot be similarly traced back to the energy radiated by the Sun.

In particular do all the energy sources exploited by civilization have a solar origin. As yet, it is true, the direct utilization of solar heat, as for instance when collected by large concave mirrors, is employed only in a few tricky devices—to run the refrigerators of cold-drink stands in the Arizona desert, or to heat water for the public baths of the oriental city of Tashkent. But when we burn wood, coal, or oil in our heating-plants and factories we are also merely liberating the energy of solar radiation that has been deposited in the form of carbon compounds in the forests of today or of long-past geological epochs.

* A fictitious character created by the idle imaginings of the Russian poets Count Alexei Tolstoy and the brothers Gemchushnikov. Prutkov's philosophic views are, however, at least as good as those of many ancient and contemporary philosophers.

The rays of the Sun, falling on the green leaves of growing plants in the presence of the carbon dioxide of the air, decompose the latter into carbon and gaseous oxygen. The oxygen is liberated back into the atmosphere (that is why plants in a room "refresh" the air), whereas the carbon is deposited in the body of the plant, ready to unite again with atmospheric oxygen in a wood fire or in a furnace.

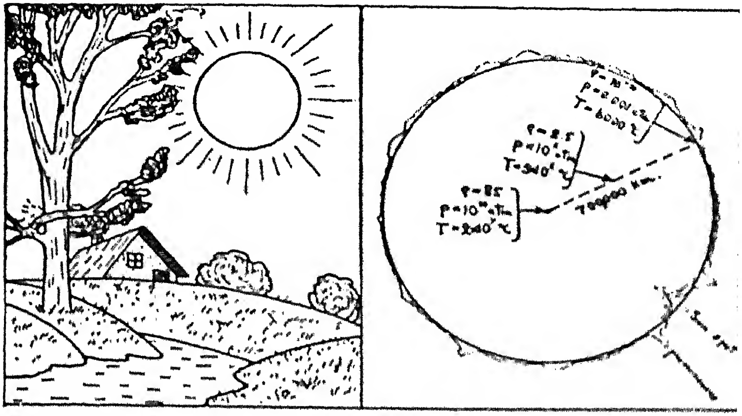

FIGURE 1

The Sun at first sight. A cross-section of the Sun.

When we burn the tree we can never get back more energy than its growing leaves had received and stored up from the solar rays. Thus, without sunlight there would be no forests, either now or in the past, and consequently no coal and oil deposits on the surface of the earth.

It should hardly be necessary to explain that water power is also a converted form of solar heat, which evaporates the water from the surfaces of oceans and seas and deposits it on higher levels from which it runs back to its original reservoirs. The same applies to wind power, which

is caused by the uneven heating of the different parts of the earth's surface, with a consequent movement of air. Everywhere we find the source of our energy to be the Sun, without whose rays the surface of our globe would be dead and motionless.

But what are the sources of solar energy? For how long have they been welling up, and how long will they go on doing so? How did our Sun come into being, and what will happen to it after all its energy resources are finally exhausted? To answer these questions we must, first of all, know something of the energy radiated daily by our Sun, and also of the total amounts of energy stored in its interior.

THE UNIT OF ENERGY

In physics energy is usually measured in standard units known as *ergs*, although in special cases other units—as calories (in heat measurements) or kilowatt-hours (in electrotechnics)—are also often employed. One erg is twice the kinetic energy of a mass of one gramme moving with the velocity of one centimetre per second, and is comparatively a very small unit as far as our ordinary experience is concerned.

For example, a flying mosquito possesses kinetic energy of several ergs; to warm a cup of tea we need several hundred billion ergs; and an ordinary table lamp uses 25 billion ergs each second. One gramme of good coal liberates in the process of complete combustion 300 billion ergs of energy, and, at present coal prices, one erg of energy delivered in bags at our coal pits costs about 0.000,000,000,000,003 cent. The price of the energy that comes to our houses along electric wires is higher, owing

to the additional cost of the machinery that transforms the heat liberated by burning coal into the energy of electric current.

THE RADIATION ENERGY OF THE SUN

The energy of solar radiation that falls each second on one square centimetre of the earth's surface perpendicular to the direction of the rays has been measured at 1,350,000 ergs, this value having been corrected for the absorption of our atmosphere. Thus, if we evaluate this energy in current coal prices, we find that on sunny days an average-sized backyard receives several dollars' worth of energy. Expressed in technical units of work, the flow of solar energy falling on the surface of the earth is equivalent to 4,690,000 horsepower per square mile; and the total amount of energy given yearly to our planet by the Sun is several million times the annual world production of energy obtained by burning coal and other fuels.

But the earth collects only a very small fraction of the total energy radiated by the Sun, the largest part of which escapes freely into interstellar space and amounts to 3.8×10^{33} ergs per second, or 1.2×10^{41} ergs per year.* Dividing this energy radiation of the Sun by its surface area (6.1×10^{22} square centimetres) we find that each square centimetre of the Sun's surface emits 6.2×10^{10} ergs per second.

THE TEMPERATURE OF THE SUN

How hot must the surface of the Sun be in order to give rise to such intense thermal radiation? A very hot radiator

* In physics and astronomy it is customary to express very large and very small numbers by the powers of ten. Thus $3 \times 10^4 = 3 \times 10{,}000$ (i.e., four zeros), or 30,000; and $7 \times 10^{-3} = 7 \times .001$ (i.e., three decimal places), or 0.007. A "billion," as used in this work, is a thousand million, or 1,000,000,000, or 10^9.

of a water-heating system (at the boiling-point temperature) radiates about one million ergs per second per square centimetre of surface. The corresponding radiation of a red-hot stove (at about 500° C.) amounts to 20 million ergs, and that of a white-hot filament of an ordinary electric bulb (at about 2000° C.) to 2 billion ergs. The radiation of hot bodies regularly increases with their temperature, being proportional to the fourth power of the temperature as counted from absolute zero.*

If we compare the surface radiation of the Sun with the examples given above, it is easy to calculate that *the temperature of the solar surface must be very close to 6000 degrees*. This temperature is considerably higher than those obtainable under laboratory conditions by the use of specially constructed electric furnaces; indeed, there is a very simple reason why no furnace could stand so high a temperature: at 6000 degrees all the materials from which a furnace might be constructed, including even such refractory substances as platinum or carbon, will be not only melted but completely evaporated.† No material can exist at these high temperatures in a state other than gaseous, and this is exactly what we find on the surface of the Sun, where all elements are present in vapour form.

But if this is true for the surface of the Sun, it must be also *a fortiori* true for its interior, where the temperatures must be still higher in order that there be the temperature

* Absolute zero on the Centigrade scale is 273 degrees below the freezing-point (see below, p. 27). Hereafter all temperatures given will be assumed to be in the Centigrade scale.

† By the utilization of this very principle, temperatures *higher* than that of the Sun's surface have actually been attained. Very strong electric currents are sent through thin metallic filaments, which at the moment of discharge are instantaneously evaporated, and, for a very short interval of time, temperatures as high as 20,000 degrees have been registered.

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difference necessary for the flow of heat from the central regions toward the surface. In fact, a study of intrasolar conditions indicates that *the temperature in the centre of the Sun reaches the tremendous value of 20 million degrees.* It is a little difficult to appreciate the significance of such high temperatures, so it may perhaps be of some help to point out that an average-sized stove (made of some non-existent refractory substance capable of withstanding such heat) if brought to this temperature would by its thermal radiation burn up everything within a radius of many hundred miles.

THE DENSITY OF THE SUN

These considerations of solar temperature have brought us to the very important conclusion that *our Sun is a giant sphere of an extremely hot gas,* but it would be erroneous to imagine this gas as necessarily being a very rarefied state of matter. Under normal terrestrial conditions the gases with which we usually deal are much less dense than the liquid or solid forms of matter, but we must not forget that the pressure in the central regions of the Sun reaches the tremendous value of 10 billion atmospheres. Under such conditions any gas will be so compressed that its density may even exceed those of normally liquid or solid bodies. For the difference between the gaseous state on the one hand and the liquid or solid states on the other lies not in their relative densities but in the tendency of the gas toward an unlimited expansion and in its high compressibility under the action of external pressure. While a piece of rock taken from the interior of the earth will hardly change its volume when brought to the surface, the material

from the central regions of the Sun will expand without limit if the outside pressure is sufficiently reduced.

The high compressibility of the gaseous matter in the Sun brings about a rapid increase of density as we go from the surface toward the centre, and it has been calculated that the central density of the Sun must exceed its mean density by a factor of 50 (that is, the core of the Sun is 50 times denser than is the Sun taken as a whole). Since the mean density of the Sun, calculated by dividing its known mass by its dimensions (mass 2×10^{33} grammes; volume 1.4×10^{33} cubic centimetres), amounts to 1.41 times the density of water, we conclude that *the gas filling the solar interior is compressed to a density six times that of mercury.* On the other hand the outer layers of the Sun are quite rarefied, and the pressure in the chromosphere, where the absorption lines of the solar spectrum are formed, is only one-thousandth the pressure of atmospheric air.

Although all our direct observational evidence concerning the physics and chemistry of the Sun is limited to the phenomena taking place in this rarefied solar atmosphere, it is possible, if we start with these surface conditions and make use of our general knowledge concerning the properties of matter, to learn about the conditions existing in the solar interior almost with the same certainty as if we could see it with our own eyes. Our mathematical analysis of the solar interior is mainly owing to the work of the British astronomer Sir Arthur Eddington; and Figure 1 gives us the schematic picture of the internal structure of the Sun as obtained from his calculations. In this picture the values of T, P, and ρ give the temperatures, pressures, and densities respectively at different depths under the surface of the Sun.

SURFACE PHENOMENA ON THE SUN

The features of solar activity most familiar to the general public are the so-called *sunspots* (Plate IA) and *solar prominences,* the eruptions of hot and luminous gases that sometimes rise to a height of hundreds of thousands of kilometres above the Sun's surface (Plate IB). The spots, which look dark only because of their contrast with the more luminous surface around them, are actually great funnel-shaped vortices in the outer layers of the Sun, within which the gases ascend spirally upwards and outwards. The expansion of the gases as they rise through these vortices decreases their temperature and makes the spots seem darker than the rest of the unperturbed surface.

When the spot is situated close to the edge of the disk, we can see these gaseous eruptions in profile as giant columns of fire. The current theory of the origin of sunspots is based on the fact that the Sun, not being a rigid body, rotates with different angular velocities in its different parts; the rotation is somewhat slower in the equatorial regions than in the regions closer to the poles. This difference of velocities causes the *formation of whirls* on the surface of the Sun, in the very same manner that the different velocities of water currents cause whirls on the surface of rapid rivers and streams.

We cannot leave the subject without calling attention to the remarkable periodicity of sunspots, a phenomenon which has not yet received any satisfactory explanation. In an average period of about eleven and a half years, there is a cyclic increase and decrease in the number of spots on the solar surface. This periodicity has some minute influence on the physics of our globe, manifested in slight changes of the average yearly temperature (within one de-

…al sunspot group (Mt. Wilson Observatory, 1917). The … represents the relative size of the earth. (See p. 8.)

PLATE IB. Solar prominence, 225,000 kilometres high (Mt. Wilson Observatory, 1917). The white disk represents the relative size of the

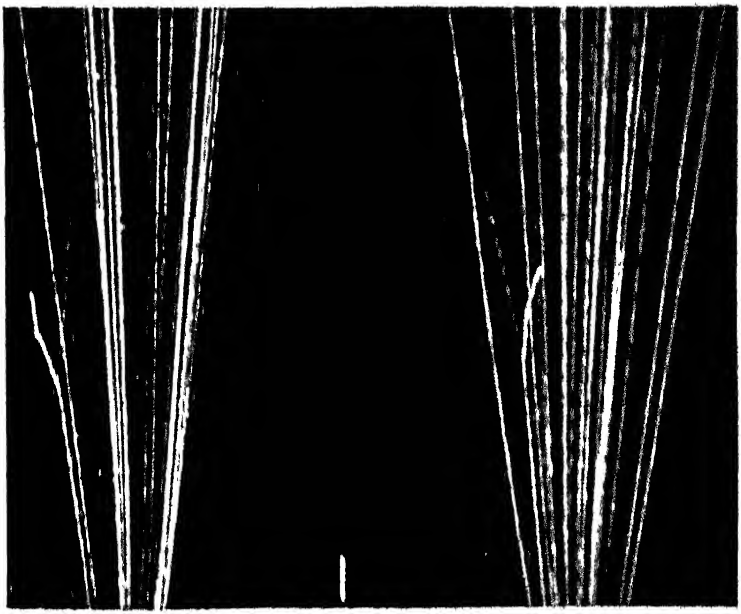


PLATE II. One of the first photographs (Blackett's) of artificial nuclear disintegration. An α-particle hits a nitrogen nucleus in the atmosphere, and ejects a fast proton (compare Figure 18). The view at the right is the one described in the text. (See p. 71.)

gree), magnetic disturbances, and the aurora. There have also been some attempts to correlate this periodic activity of the Sun with changes in the time of the migration of swallows, with wheat yields, and even with social revolutions, but such correlations can hardly be considered as well established.*

Spots and prominences are limited to a comparatively thin layer of the solar surface, and probably have no more connexion with the evolutionary life of the Sun than slight skin irritations have with the developmental life of human beings. Thus, the group of problems represented by these phenomena will not concern us in the present book.

THE AGE OF THE SUN

We come now to the important question of the age of the Sun, which is, on the one hand, closely connected with the problem of the age of our earth and, on the other, with that of the age of the entire stellar universe. We know that the Sun of today is the same as it was last year, the same as it was when Napoleon pointed it out to his soldiers as the "Sun of Austerlitz," the same as it was when the priests of ancient Egypt worshipped it as Amon-Ra, the God of Gods.

Of course, the period of recorded human history is only a quick wink as compared with the geological and palæontological time scale, and the evidence hidden under the surface of the earth suggests a considerably longer period

* Registered maxima occurred in the years 1778, 1788, 1804, 1816, 1830, 1837, 1848, 1860, 1871, 1883, 1894, 1905, 1917, 1928. And, as a matter of fact, the American Revolution, the French Revolution, the Paris Commune, both Russian Revolutions, and also some others fell fairly close to the years of maximum solar activity. There has also been a distinct increase in activity lasting persistently through 1937–1940, which, if the reader wishes, he may tentatively associate with the highly perturbed state of the world during these years.

during which the Sun's activity has remained unchanged. The coal we burn in our stoves today gives us excellent proof that the same Sun shone above the strange-looking forests of lepidodendrons and giant horse-tails of long past geological epochs; the fossils found in different geological layers exhibit an unbroken course of organic evolution since pre-Cambrian times. During the past several hundreds of millions of years, therefore, the Sun cannot have changed in its brightness by an appreciable amount, for any appreciable change would have made life on earth quite impossible and cut short the progress of organic evolution.* Indeed, halving the amount of solar radiation would bring the earth's temperature well below the freezing-point, and multiplying it by four would cause the oceans and seas to boil.

Life on earth must surely be younger than the earth itself, and still larger age-estimates can be derived from the purely inorganic evidence contained in the chemical constitution of the rocks that form the crust of our planet. Many of these rocks contain minute amounts of the so-called radioactive elements, uranium and thorium, which are known to be unstable and to decay very slowly—a process which takes billions of years and leads to a final product analogous to ordinary lead. As long as the surface of the earth was in a molten, lava-like state, these disintegration products must have been constantly separated from their mother-elements by the mixing processes of diffusion and convection; but, as soon as the solid crust had been

* The possibility is not excluded that the so-called glacial periods, indicated by geological evidence, may have been connected with some small variation of solar activity. It should be noted, however, that such small changes of climate could also be easily produced by purely terrestrial factors, as, for example, the variation of the carbon-dioxide content in our atmosphere.

formed, they must have begun to accumulate near the radioactive elements. Therefore, by measuring the relative amounts of these radioactive elements and their disintegration products in different rocks, we can form an exact idea about the time when the rock became solidified, in the same way as we might estimate the age of a village from the number of bones in its cemetery.

The investigations carried out along these lines lead to the conclusion that *the solid crust of the earth was formed not later than 1.6 billion years ago*. Since the formation of the crust must have taken place rather soon after the separation of the earth from the Sun, we also have by this means a fairly exact estimate of the age of our planet as an individual body. The Sun cannot be younger than this, but it may be considerably older, and, in order to put an upper limit on its possible age, we must turn to the evidence concerning the whole stellar universe of which our Sun is only one of numerous members.

The process of the formation of stars, and in particular of our Sun, from a uniform gas previously filling all space, will be discussed in later chapters (X–XII). Here we shall merely mention that the study of the motion of stars in our stellar system, and of the motion of different stellar systems relative to one another, strongly suggests that *the process of star formation took place not earlier than 2 billion years ago*. This gives us rather narrow limits for the probable age of the Sun; it also indicates that our earth and other planets must have been formed during an early phase of the Sun's life.

Multiplying the annual radiation of the Sun as given above (1.2×10^{41} ergs) by its estimated age in years (approximately 2 billion), we arrive at the conclusion that

since its formation the Sun must have radiated about 2.4×10^{50} ergs of energy, or 1.2×10^{17} ergs for each gramme of its mass. Where did these tremendous amounts of energy come from?

DOES THE SUN REALLY "BURN"?

The first hypothesis concerning the origin of solar heat and light was most probably uttered by some caveman of the Early Stone Age who, looking at the shining Sun, applied to it the same word that he used to denote the burning fire of his hearth. Prometheus, when he stole a piece of the eternal fire of the Sun for early man, probably considered it to be just as good for cooking purposes as the fire fed by wood or coal. And this naïve belief that the Sun "burned" firmly held its place in the mind of humanity up to comparatively recent times.

The moment, however, we ask what it actually is that burns in the Sun, it becomes evident that the process of ordinary combustion is quite inadequate to explain the long period of solar activity. We have already seen that a gramme of coal when completely burned develops only 3×10^{11} ergs, which is half a million times less than the energy production per gramme of the Sun during its past life. If the Sun were made of pure coal and had been set afire at the time of the first Pharaohs of Egypt, it would by now have completely burned to ashes. The same inadequacy applies to any other kind of chemical transformation that might be offered in explanation of solar heat development; none of them could account for even a hundred-thousandth part of the Sun's life.

As a matter of fact, the very notion of "burning" is quite inconsistent with the conditions to be found in the Sun.

Spectroscopic analysis does show the presence of both carbon and oxygen in the solar atmosphere, but *the Sun is just too hot to burn.* Ordinarily we are accustomed to think of combustion, or of any other chemical reaction resulting in the formation of complex compounds, as facilitated by an increase in temperature. A piece of wood will begin to burn, that is, to unite with the oxygen of the air, when it is set afire by the flame of a match, and to light a match we have to heat the phosphorus of its head by rubbing it against a rough surface; but too high temperatures are, on the other hand, *destructive* to complex chemical substances and cause their dissociation into elements—water vapour being decomposed into hydrogen and oxygen, carbon dioxide into carbon and oxygen.

The temperature of 6000 degrees to be found in the solar atmosphere breaks the chemical bonds of all complex compounds, and *the gas forming the Sun must consist only of a mechanical mixture of pure elementary substances.* In the outer layers of some other stars, however, with considerably lower surface temperatures (1000 to 2000 degrees) the formation of complex substances, including carbon dioxide, could be expected to take place.

THE CONTRACTION HYPOTHESIS

We have gone somewhat afield from our original question concerning the origin of solar energy, and in returning to our theme we are brought to the work of a famous German physicist of the last century, Hermann von Helmholtz, who was concerned not only with the problem of the present state of the Sun, but also with that of its origin.

According to Helmholtz, the Sun was, once upon a time, a giant sphere of cool gas with a diameter much larger

than its present one. It is clear that such a gas sphere could not be in a state of equilibrium, for the comparatively slight pressure of a cool and highly rarefied gas could not balance the mutual gravitational attraction among its different parts. Thus, under the action of its own weight, this primitive Sun must have started a rapid contraction, compressing the gas in its interior regions. But it is well known from elementary physics that the compression of a gas, as by a moving piston in a cylinder, causes a rise of its temperature. Thus, the progressive contraction, or falling in, of the original giant gas-sphere must have caused the heating of its material, until the rising pressure of the gas in the interior became great enough to hold up the weight of the outer layers.

At this stage the rapid falling-in process of the solar substance must have been stopped, and the Sun would have come to a perfect equilibrium if there were no loss of energy from its surface. But, owing to the continuous radiation from the surface into the surrounding cold space, our gas-sphere will be constantly losing some energy, and, to compensate these losses, a further progressive contraction becomes necessary. According to the Helmholtz point of view, then, the Sun is actually in this state of progressive contraction, its radiation being due not to any chemical action but entirely to the gravitational energy liberated in this process.

From Newton's laws of gravity, it is not difficult to calculate that, in order to maintain the observed intensity of solar radiation, the Sun's radius must decrease every century by 0.0003 percent, or by approximately two kilometres. Such a change would, of course, pass quite unnoticed, not only during the life of a given individual, but

also during the entire period of human history. Nevertheless, from the point of view of the geological time scale, it is much too rapid.

The total gravitational energy that would have been liberated in the contraction of the Sun down to its present radius, even from almost infinite dimensions, can be calculated: it is only 2×10^{47} ergs, which still gives us 1000 times less energy than has actually been expended. Thus, although it seems very likely that Helmholtz's contraction hypothesis may quite correctly account for the early stages of solar evolution, we must conclude that *in its present state our Sun possesses other energy sources much more powerful than those of chemical or gravitational origin.*

SUBATOMIC ENERGY

The physical science of the last century was quite unable to explain the riddle of the energy supply of our Sun; but on the verge of the present century, the discovery of the phenomenon of the radioactive decay of matter, and with it the possibility of the artificial transmutation of elements, threw some light on this most fundamental question of astrophysics. It was found that in the very depths of matter, inside the infinitesimal nuclei of the atoms of which all material bodies are constituted, tremendous amounts of energy lay hidden. This so-called *subatomic energy,* which was first observed slowly leaking out from the atoms of radioactive bodies, may under certain circumstances flow out in a vigorous stream surpassing by a factor of millions the energy production of ordinary chemical reactions.

The study of subatomic energy and of the physical conditions necessary for its liberation has permitted us in

recent times to account not only for the radiation of our Sun but also for the radiation and other characteristic properties of the various types of stars known to the astronomer. Furthermore, the questions concerning stellar evolution, and in particular the question about the past and future of our own Sun, have been brought much nearer solution since the problem of energy sources was solved.

But, before we may approach the discussion of these exciting problems, we must first make a long detour through the world of atoms, and learn certain important things about their properties and internal structure. The author regrets the pain that this excursion into the domain of pure physics may cause some readers who picked up this book for its astronomical title, but, except for poets, no one should speak about stars without knowing the properties of matter of which they are constructed. Besides, if the reader pays close attention to the rather difficult subjects to be discussed in the next three chapters, he will be rewarded by a better understanding of astronomy, of which we promise there will be plenty in the chapters that follow them. And, finally, it is possible merely to skim through these three chapters and to take their conclusions for granted without thereby sacrificing a clear picture of the evolutionary past, present, and future of our Sun.

The Anatomy of Atoms

THE ATOM AS PHILOSOPHIC IDEA

THE history of atomic theory begins in the ancient Greek city of Abdera, approximately in the year 375 B.C. Its first proponent was an elderly man with an untidy grey beard who taught his doctrines outdoors, in the shadow of the temple. Democritus was his name, and he has been known as the Laughing Philosopher.

"Any piece of matter, as for example this stone," we may imagine him lecturing, "is constructed of a great number of extremely small separate particles, in the very same way that this temple is constructed of its separate stones. These particles, constituting all material bodies, come together in different order and positions, like the letters of the alphabet, which, though they are few, form innumerable words. These basic particles represent the last thinkable step in the divisibility of matter. Thus, I call them *atoms* (that is, 'indivisible'). They are so small that it must be logically impossible to divide them into still smaller parts."

For the philosophic mind of Democritus, the existence of atoms was a logical necessity, the last step in the process of the successive division of matter, a process that he refused to recognize as being unlimited. The atomic hypothesis also appeared to him to reduce the infinite variety of observed phenomena to the combinations of a comparatively few types of elementary particles, and thus to satisfy

his philosophic preconception concerning the fundamental simplicity of nature.

In conformity with the ideas prevailing at this time in Greek philosophy, Democritus recognized four different types of basic particles: those of air, earth, water, and fire, which represented respectively the properties of lightness, heaviness, dampness, and dryness. He believed that all the known substances of nature could be obtained from different combinations of these four basic elements, as in the ordinary processes of making mud from a mixture of earth and water, or vapour from a "mixture of fire and water" in a saucepan. He even speculated about the properties of these basic particles and, in particular, imagined the "atoms of fire" as slippery spherical bodies, thus explaining the liveliness of flame.

ALCHEMY AND THE MEDIEVAL GOLD-FEVER

Many centuries passed after the time of the Greek thinker who had sought to penetrate into the riddles of matter by the sheer power of mind before the study of matter and its transformations took a more practical turn. Throughout the Middle Ages, in rooms dimly lit by dusty Gothic windows, the alchemists of Europe toiled vainly before great fireplaces, with innumerable odd-shaped retorts, with jars of every conceivable substance. Ridden by the old philosophic doctrine of the unity of matter, and by the practical desire to enrich themselves, they powdered, mixed, melted, dissolved, boiled, precipitated, sublimated, and treated in every possible manner these various substances of nature in a desperate search for a method of making artificial gold; and thereby they incidentally laid the foundations of modern chemistry.

At this time the four "elements" of ancient Greek philosophy had been replaced by four other supposedly elementary substances: mercury, sulphur, salt, and fire. It was believed that their proper combination must finally lead to the formation of gold, silver, and all other known substances. But as gold and silver stubbornly refused to be formed in spite of the centuries-long efforts of hundreds of alchemists, the conception began slowly to be advanced in many alchemical laboratories toward the end of the seventeenth century that these precious metals, as well as many other substances, were themselves also elementary. It was thus that the mysterious art of making gold eventually developed into the science of chemistry, and the four elementary substances of alchemy and philosophy gave place to a larger but still limited number of independent chemical elements.

So persistent was the effect of the negative results of medieval alchemy, however, that in the chemistry of the eighteenth and nineteenth centuries the impossibility of transmuting one element into another was considered to be a basic principle of the science. The atoms of the different elements were thought of as absolutely indivisible particles of matter, in complete agreement with the Greek meaning of their name, and "alchemist" became a word of reproach among scientists. But, as we shall see later, the pendulum of theory had swung much too far in the opposite direction.

ELEMENTARY CHEMISTRY

If there is only a limited number of different kinds of atoms (we know now that there are ninety-two elements), then all the vast number of other substances must be com-

posed of different combinations of these atoms; and the complex constituent particles, or *molecules*, of the various chemical non-elementary substances must differ only in the kind and relative number of the atoms of which they are constructed. It is known at present to every schoolboy, for example, that the molecule of water consists of two hydrogen atoms and one oxygen atom, and that, on the other hand, the molecule of hydrogen peroxide—familiar to all brunettes envious of platinum blondes—consists of two hydrogen and two oxygen atoms. In the latter molecule, the second oxygen atom is bound comparatively loosely and can easily become free, thereby causing the oxidation and discoloration of different organic substances. The process by which a complex, unstable molecule of hydrogen peroxide is dissociated into a molecule of ordinary water and a free oxygen atom is shown schematically in Figure 2.

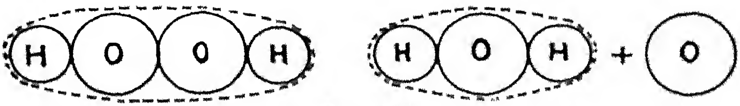


FIGURE 2
Dissociation of hydrogen peroxide into water and free oxygen.

In order to save time, chemists prefer to express such processes in a somewhat simpler fashion, employing formulas in which each element is denoted by a symbol (an abbreviation of its Greek or Latin name), and in which the number of atoms of each kind in a given molecule is indicated by a small figure at the lower right-hand corner of the corresponding symbol. The chemical reaction described above can thus be written in the form:

$$H_2O_2 \longrightarrow H_2O + O$$

In the same way we write CO_2 for the carbon dioxide of the air, C_2H_5OH for alcohol, $CuSO_4$ for the blue crystals of copper sulphate, and $AgNO_3$ for lunar caustic, or silver nitrate.

The atomic-molecular hypothesis obviously requires that the relative amounts of different chemical elements necessary for the formation of any complex chemical substance should always be in the same proportions as the weights of the corresponding atoms, and the experimentally established fact that this is really so serves as one of the best proofs for the correctness of these views. This theory was first propounded by the English chemist John Dalton at the very beginning of the last century.

"Suppose," Dalton had argued, "that old Democritus were right, and that all elementary bodies do really consist of infinitely small atoms. If one were to go about constructing a particle of some chemical compound from these atoms, one should have to use one, two, three, or more of them. But one cannot use, say, three and a quarter atoms, just as one cannot build a gymnastic group out of three and a quarter acrobats." After the publication in Manchester, in 1808, of Dalton's book, *New System of Chemical Philosophy,* the existence of atoms and molecules became the established and unshakable basis of the science of matter. The quantitative study of chemical reactions among various elements led to the exact evaluation of their *relative atomic weights,* but the absolute weights and dimensions of individual atoms remained outside the scope of chemical science. The further progress of atomic theory now depended upon the development of the science of physics.

THE KINETIC THEORY OF HEAT

Does the hypothesis of the molecular structure of matter permit us to understand the differences between its three fundamental states—the solid, the liquid, and the gaseous? We know that any substance in nature can be brought into each of these three states. Even iron evaporates at several thousand degrees, and even air freezes into a solid block at sufficiently low temperatures. Thus, the difference between the solid, liquid, and gaseous states of a given body depends upon its thermal condition. By adding heat to a solid body we transform it into a liquid. By adding still more heat we transform the liquid into a gas. But what is heat?

In the early stage of the development of physics, it was thought that heat was a unique imponderable fluid that flowed from hot bodies into colder ones, warming them; a point of view that represented a survival of the ancient idea of fire as an independent element. But we can warm our hands simply by rubbing them against each other, and a piece of metal becomes hot if we strike it many times with a hammer. It seemed strange that this hypothetical "heat-fluid" should be produced by rubbing or striking.

From the molecular theory of matter came a much more rational explanation, according to which a hot body does not contain any additional fluid of any kind, but differs from a cold body only in the state of motion of its particles. *The molecules of every material body at normal temperature are in a state of permanent motion; and the faster they move, the hotter the body seems.* If we bring a hot body into contact with a colder one (or, as we say, if there is a *temperature gradient* between two adjacent bodies), the fast-moving molecules of the first will collide, on their common boundary, with the slower-moving molecules of

the second and transfer to them a part of their kinetic energy. Thus, the fast molecules will gradually slow down, and the slow ones speed up, until a state of equilibrium will be reached in which the molecules in both bodies have equal average energies. We say then that both bodies possess the same temperature, and that the "flow of heat" from one into the other has ceased.

From such a view of the nature of heat and temperature, it follows at once that there should exist *a lowest possible temperature, or an absolute zero,* at which the molecules of all material bodies are completely at rest. At this temperature the constituent particles of any substance will stick together, because of intermolecular cohesive forces, and demonstrate the properties of a solid.

As the temperature rises, and the molecules begin to move, there comes, sooner or later, a stage when the cohesive forces are no longer able to keep the molecules rigidly in their places, though still strong enough to prevent them from flying apart. The body ceases to be rigid but still keeps its finite volume, and we then have matter in the liquid state. At still higher temperatures, the molecules move so fast that they tear apart from each other and fly off in all directions, thus forming a gas with a tendency toward unlimited expansion. The fact that some substances melt and evaporate at much lower temperatures than others is simply explained by differences in the strength of the cohesive forces of their respective molecules.

THE ENERGY OF MOLECULAR MOTION

Is there a direct empirical confirmation for these views; may one actually observe this, thus far hypothetical, thermal motion of molecules? The first step toward such a proof

was actually made early in the nineteenth century, but the man who made it had not the slightest idea of the importance of his discovery.

Robert Brown, F.R.S., D.C.L., keeper of the botanical collections of the British Museum in London, was bent over his microscope, watching with great surprise the strange behaviour of certain tiny plant spores suspended

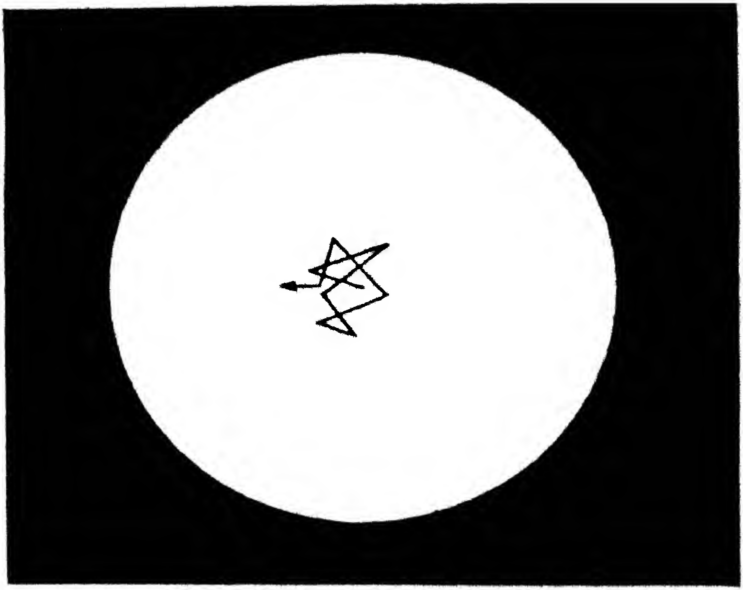


FIGURE 3
The trajectory of Brownian motion as seen through a microscope.

in a little drop of water. The spores seemed to be animated by a continuous but irregular motion; they jumped to and fro and described complicated zigzag trajectories though they never went far from their original positions (Figure 3). It was as if all the inside of the drop were shaking, as things do on a fast train; yet the microscope on the old botanist's

table stood quite steady. This property of permanent restlessness is typical of any kind of very small particle suspended in a fluid; it was later found to hold for tiny metallic particles suspended in water (the so-called *colloid suspension* of metals) and even for miniature dust particles floating in the air.

Brown announced his discovery in 1828, but could give no adequate explanation for it. Almost half a century later it was shown that the cause of this *Brownian motion* is the continual irregular bombardment of the suspended particles by molecules of the liquid or gas animated by thermal motion. The minute "Brownian particles" are just half-way in size between the invisibly small molecules and the objects we deal with in everyday life; they are small enough to be influenced by collisions with separate molecules, but still large enough to be seen through a good microscope. By examining the motion of these particles we can directly calculate the energy of thermal motion of the surrounding molecules. And the fundamental laws of mechanics tell us that, in a mixture of a great number of irregularly moving particles, they must all have, on the average, the same kinetic energy; the lighter particles must move faster and the heavier ones more slowly in such a way that the product of their individual masses by the square of their individual velocities (which product defines the kinetic energy) remains always the same.

If this *equipartition law of energy* is not fulfilled in the beginning, the mutual collisions will very soon slow down the particles that move too fast and speed up those that move too slowly, until the total energy is equally divided among all of them. The Brownian particles, although they seem very small to us, are quite gigantic as compared with

separate molecules, and must consequently have a considerably slower motion. Observing the velocity of motion of these particles, and also, by an ingenious device, measuring their mass, the French physicist Jean Perrin was able to show that *at room temperature* (20° C. or 68° F.) *their average kinetic energy amounts to* 0.000,000,000,000,063 (i.e., 6.3×10^{-14}) *erg*. According to the equipartition law,

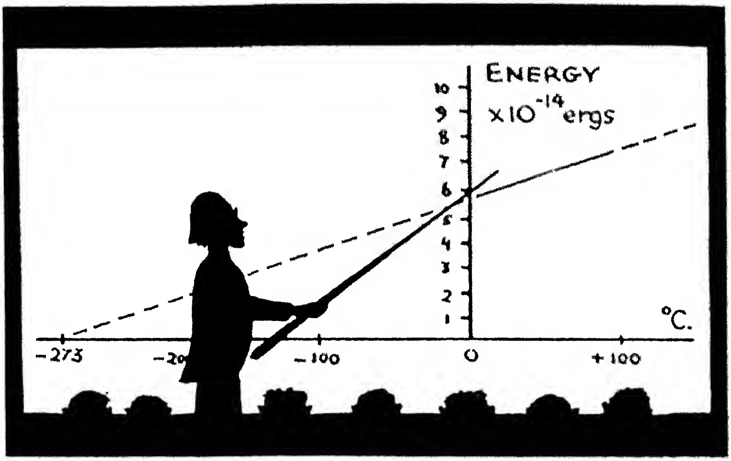


FIGURE 4
The thermal energy of molecules decreases with the temperature, and vanishes at −273° C.

this must also be the kinetic energy of the molecules of any substance at this temperature.

The study of Brownian motion permits us also to correlate the increase of molecular motion with the rise in temperature. If we heat the liquid in which the particles are suspended, their motion becomes more and more animated, showing the increasing energy of the motion of separate molecules. In Figure 4 we illustrate the depend-

ence of the measured energy of Brownian particles (or, what is the same thing, of the separate molecules) upon the temperature of the liquid. For water the measurements can, of course, be made only between the freezing- and boiling-points (see the unbroken line between 0° and + 100°); but, since all the observed points between these limits are found to lie on a straight line, we can *extrapolate* this line for lower and higher temperatures, that is, continue it in both directions, as in the dotted part of the line in Figure 4.

Being extrapolated toward the lower temperatures, the observed line crosses the horizontal axis, representing zero energy, at the point —273° C. (—459° F.). At this point the energy of molecular motion absolutely vanishes, and below this point it is therefore meaningless to speak of differences in temperature. It represents the lowest possible temperature, or *absolute zero,* and is the foundation of the so-called *absolute, or Kelvin's, temperature scale.*

MEASURING THE MOLECULAR VELOCITIES

Since the study of Brownian motion has led us to a direct estimate of the kinetic energy of the thermal motion of molecules, we need only find a method for directly measuring the velocities of molecules, and from these two measurements we shall readily estimate also their mass (since kinetic energy = ½ mass × square of velocity). A very excellent method for the direct estimation of molecular velocities was worked out by a skilful German physicist, Otto Stern. Stern knew that one could hardly hope to measure the velocities of molecules within a gas or a liquid, where, owing to the never-ending mutual collisions, the particles move too irregularly and their velocities are constantly

changing direction. In the air, for example, under normal pressure and temperature, each molecule is subjected to many billions of collisions per second, and the free path between two collisions measures only 0.000,01 centimetre.

The problem Stern set himself, therefore, was to give a few gas molecules unobstructed and measurable paths in free space; and in a few months he devised a new apparatus for this purpose (Figure 5). All the parts of this apparatus

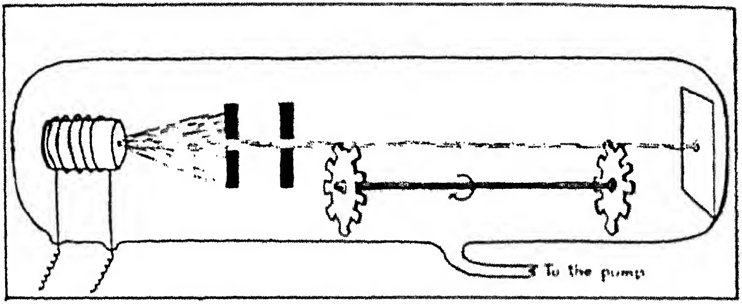


FIGURE 5
Diagram of Stern's apparatus for the measurement of molecular velocities.

were placed inside a long, cylindrical, completely evacuated vessel. At one end (left) of this large cylinder was a "molecular dungeon," a closed chamber into which was placed (through a special valve in the back) the substance to be investigated. A wire wound spirally around this chamber carried an electric current which developed enough heat to evaporate its contents. As the molecules of the vapour, animated by thermal motion, flew about in all directions inside the dungeon chamber, some of them were bound to escape, through the tiny hole provided in its wall, in a fine molecular spray. In front of the opening, however, two little diaphragms cut out from this spread-

ing molecular beam all except those particles which were moving along the axis of the cylinder. *Thus was formed a parallel beam of molecules, all moving in the same direction with their original thermal velocities.*

But the essence of the device was the means for actually measuring the velocity of the particles forming this beam. For this purpose Stern borrowed a method often used to regulate automobile traffic on long avenues of large cities, in which the traffic lights are so synchronized that only the cars driven at a certain speed can go all the way through without being stopped by red lights at intersections. In Stern's apparatus this same stop-and-go system was set up as follows:

In the path of the parallel beam of molecules two cogwheels, fastened on opposite ends of a rapidly rotating axis, were adjusted in such a way that the teeth of the first were exactly in front of the openings of the second, so that, when the axis was not rotating, no molecule could pass through. But if the wheels were rotated at such a speed that the time in which a tooth turned by one-half its width was exactly the time required for the molecule to cover the distance between the wheels, then all the molecules of the same velocity would pass both wheels and be registered on the screen at the right end of the large cylinder. Thus, by observing the speed of rotation necessary to let the molecular beam through, Stern could easily calculate the velocity of the particles of the beam. The velocity of sodium atoms at a temperature of 500 degrees was found by him to be 100,000 centimetres per second (2000 miles per hour!), which, when recalculated for hydrogen atoms at room temperature, gives the value of 2.8×10^5 centimetres per second.

If we now remember from Perrin's experiment (p. 26) that the kinetic energy of thermal motion for all particles at this temperature is 6.3×10^{-14} erg, it is easy to calculate (from the formula: kinetic energy = ½ mass × velocity squared) that *the mass of a hydrogen atom amounts to 1.6×10^{-24} gramme.* The masses of other atoms and molecules can now also be calculated from their relative atomic and molecular weights as estimated by chemical methods. For instance, the water molecule is eighteen times heavier than the hydrogen atom, and since a cubic centimetre of water weighs one gramme, it must contain 3×10^{22} water molecules, and the diameter of a water molecule must therefore roughly be 3×10^{-8} centimetre.* To obtain some idea of the negligible weight and size given by the above quantities, one need only note that *the number of molecules in a little drop of water is about the same as the number of drops of water in the great Lake Michigan.*

STATISTICS AND THE MAXWELL DISTRIBUTION

We have mentioned above that, in any collection of a large number of irregularly moving particles, the mutual collisions must soon lead to a state in which the total energy of the system will be, on the average, equally distributed among all the particles. By the phrase "on the average" we mean to indicate that this proposition can be *only statistically true,* for, as a matter of fact, owing to the irregularity of the collisions, any given molecule may, at any given instant, be travelling at an extraordinarily great velocity or may, on the other hand, be almost motionless. Thus, the kinetic energy of any given particle is constantly

* The dimensions of a molecule can be given only with a rough average value, since, according to the present view of atomic structure, its exact limits are essentially undefined. (See Figure 14 below.)

increasing and decreasing quite irregularly, but the average value will remain the same for all the particles in the collection. If at a given instant we could measure simultaneously the velocities of all the molecules of a gas filling a vessel, we would find that, although the energies of most of the particles were very close to the average value, there

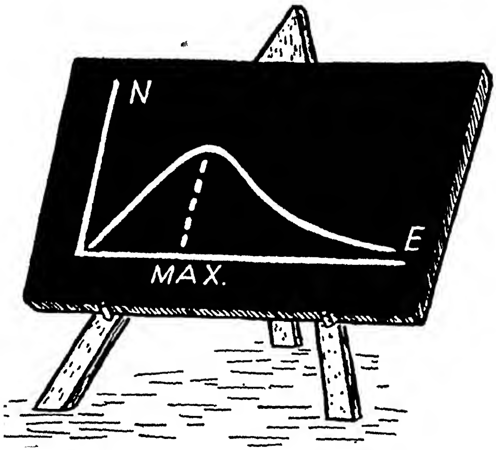


FIGURE 6
The Maxwell curve, showing the relative number of molecules with different energies at a given temperature. N = number of particles; E = energy.

would always be a certain percentage of the particles with velocities considerably smaller or larger than the average.

In Stern's apparatus, for instance, there were always found to be present in the molecular beam some particles that were moving faster or slower than the average. Experimentally this was shown by the fact that, when the speed of the rotating cogwheels was changed, the beam passing through did not immediately vanish, but its intensity decreased to zero rather gradually. This phenomenon pro-

vides us with a method for finding out how many molecules of different energies are present in the beam. This energy distribution is described by a very simple formula developed, on the basis of purely statistical considerations, by the English physicist Clerk Maxwell and known as the *Maxwell distribution law.*

The distribution, which is represented graphically in Figure 6, is quite general and applies to any large collection of particles, from the molecules of a gas in a vessel to the stars forming our galactic system. We shall see later that this distribution of molecular velocities plays an important role in the questions concerning the liberation of subatomic energy from substances brought to very high temperatures.

ARE ATOMS REALLY ELEMENTARY PARTICLES?

Ever since the establishment of the atomic theory as fundamental to the science of matter, the atom has been the carrier of all the characteristic properties of the different elements. Why is it that hydrogen will unite with oxygen and carbon, but will not form any chemical compounds with such elements as sodium or copper? Because such are the chemical properties of the atoms of these substances. Why does putting a sodium salt into a flame give rise to a brilliant yellow colour, while copper salts give off a green illumination? Because such are the different optical properties of sodium and copper atoms. Why is iron hard and strong, tin so soft, and mercury, at normal temperature, liquid? Because of the differences of cohesive forces of the atoms of these metals.

But is it possible to explain why different atoms possess such different properties? Yes, if we abandon the old idea

of the basic indivisibility of atoms, which was solemnly accepted in science up to comparatively recent times, and instead think of the atom as a complex structure built up of other, still smaller particles. Thus we may be able to relate the known properties of the atoms of different elements to the differences in their *internal* structure. But if atoms are really complex systems, what then are the particles of which they are constructed? Is it possible to make an "autopsy" of an atom, extract its various parts, and study them separately? To answer these questions we must first turn our attention to the study of electric phenomena, and particularly of the basic electric particles, or *electrons*.

ANCIENT PERSIAN ELECTROGILDING

The first practical use of electricity and electric current takes us back to the distant past. In recent excavations at

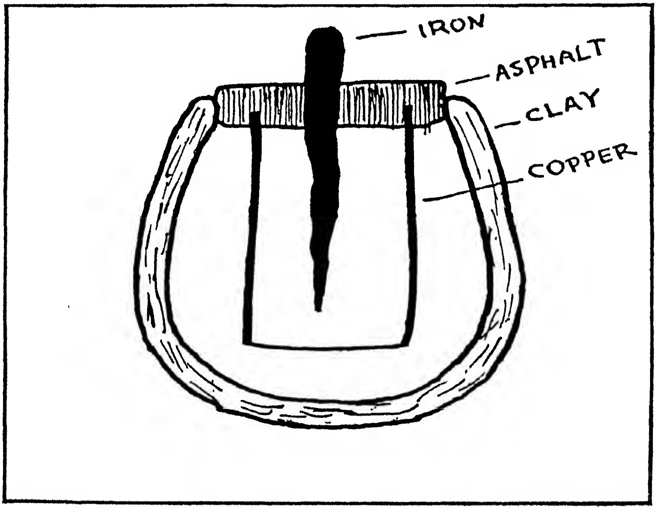


FIGURE 7
An ancient Persian electric battery.

Khujut-Rabua, not far from the city of Baghdad, a very strange type of vessel has been found among the relics that probably belong to the first century B.C. It consists of a vase, made of clay, inside of which is fastened a cylinder of pure copper. Through a thick asphalt cover on its top is driven a solid iron rod, the lower part of which has been eaten away, probably by the action of some acid (Figure 7).

This assembly could hardly have been used for any other purpose than that of generating a weak electric current, and was most probably used by Persian silversmiths, long before the reign of the fabulous Harun al Rashid, for electrogilding their wares. In the backs of little shops in colourful oriental bazaars, electric currents were depositing uniform layers of gold and silver on ear-rings and bracelets almost two thousand years before the phenomenon of electrolysis was rediscovered by the Italian Dottore Galvani and made widely known to humanity.

THE ELEMENTARY ELECTRIC CHARGE OF ATOMS

The very same process of transferring matter by electric current that had served to gild jewellery for oriental belles of long ago was the basis of some remarkable conclusions concerning the properties of matter and electricity by the celebrated English physicist of the last century, Michael Faraday. Investigating the relation between the amount of electricity that passed through an electrolytic solution and the amount of material deposited on the electrodes, Faraday found that for the same amount of electricity the deposits of different elements were always proportional to their combining chemical weights. From the atomic-molecular point of view, this means that *the electric charge carried by different atoms is always an integer multiple of*

certain elementary amounts of electricity. For example, an *ion* (that is, a charged atom) of hydrogen carries one single positive charge, an ion of oxygen a double negative charge, and an ion of copper a double positive charge.

Thus it became clear that there is some sort of *atomicity of electric charge,* paralleling the atomicity of matter. One can calculate the absolute amount of this elementary charge simply by dividing the total amount of electricity that has passed through an electrolyte by the number of hydrogen atoms deposited at the negative electrode. Expressed in customary units, this elementary portion of electricity is extremely small; for example, the current feeding an ordinary table lamp carries billions of billions of such portions every second.

THE ATOMICITY OF ELECTRIC CHARGE ON SMALL BODIES

We have previously seen that the atomicity of matter and the thermal motion of molecules are directly observable through their effects on the small, but still visible Brownian particles. Is it similarly possible to observe the discontinuity of electric charges by studying particles small enough to be influenced by very faint electric forces, yet still large enough to be seen through a microscope? Yes, this can and has been done.

One foggy day in the autumn of 1911, Robert A. Millikan, then professor at the University of Chicago, was intently looking through a microscope attached to a rather complicated assembly of cylinders, pipes, and wires. In the brightly illuminated field of the microscope, a tiny droplet was floating in mid-air, near the intersection of two cobwebs that marked the centre of the visible field. It was one

of many thousands of similar droplets under the microscope, produced by a special kind of atomizer and all together appearing to the naked eye as a little cloud of fog. Suddenly the droplet, which had been motionless for a while, started rapidly upwards, but, before it could escape completely from sight, Dr. Millikan rapidly shifted the handle of a rheostat, bringing the droplet to rest again. "Two fifty-eight," murmured his assistant, marking in his notebook the reading of the voltmeter. "One twenty-nine," he said again, following the next motion of his chief's hand; "zero eighty-six, zero sixty-four and a half. . . ." Dr. Millikan, tired from watching the droplet so steadily and keeping it in its place, leaned back in his chair.

"That was a nice run," he remarked, inspecting the record of the experiment; "just one electron at a time. I think we now have enough material to calculate the exact value of the elementary charge."

What was it all about and why was it so necessary to keep the droplet motionless under the microscope? The point is that the droplet, which had made so many attempts to run away, was simply a very small charged material body, so small that it could be influenced by electric forces acting on one elementary charge. And the adjustment of the voltage to keep it at rest was merely a method of measuring its electric charge (Figure 8).

The little cloud under Millikan's microscope was, incidentally, not the same kind of fog that was hanging that morning over the streets of Chicago. It was an "oil fog," consisting of tiny droplets of pure mineral oil, and was used instead of ordinary water fog because water droplets would gradually have evaporated and thus changed their mass during the experiment. Dr. Millikan's first problem,

after obtaining the fog, was that of picking one of the droplets up in the field of the microscope and charging it with electricity. But one cannot very well charge a body so small, almost invisible, by touching it with an ebonite stick that has been rubbed against one's woollen trousers. A good physicist, however, can always, or almost always, find a way out of such a difficulty, and Dr. Millikan did so by

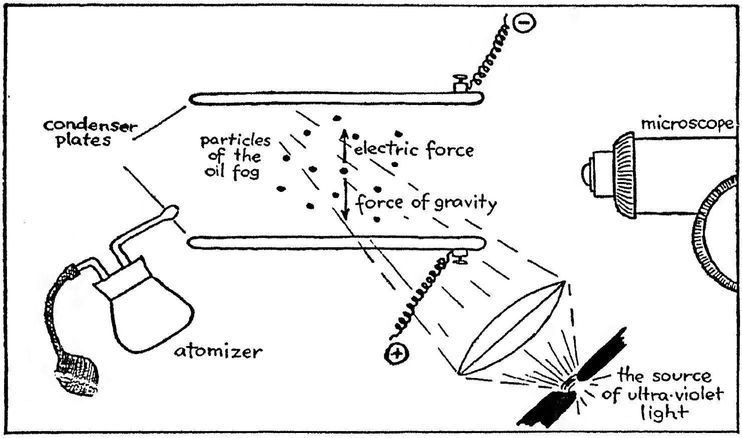


FIGURE 8
Diagram of Millikan's apparatus for the measurement of the elementary electric charge.

using for his purpose the phenomenon of *photoelectric effect.*

It is known that all bodies, when illuminated by ultraviolet rays (which are emitted, for example, in large amounts by an ordinary electric arc), lose their negative electricity and become positively charged. Illuminating his oil fog with the light of an electric arc, Millikan could induce in the droplets a positive electric charge which

changed in value from time to time. If such an electrified fog is produced between two horizontal plates of a condenser (the lower plate being charged positively and the upper one negatively), the electric force acting on the separate droplets will pull them upwards. By controlling the electric field between the plates, one can balance this upward force precisely against the weight of the droplet to make it float in the air like the coffin of Mohammed. Whenever the charge of the droplet changes under the action of ultraviolet illumination, the droplet begins to move and a new adjustment of voltage is made necessary. Knowing the applied voltage and the mass of the droplet, one can easily calculate the electric charge carried by the latter.

By making a long series of experiments of this character Millikan came to the conclusion that the numerical values of the droplet charges are always integer multiples of a certain minimum charge, the smallest ever observed. Furthermore, this minimum amount of electric charge carried by the oil droplets turned out to be exactly the same as the minimum charge of a charged atom, or ion, as estimated from electrolytic phenomena. This definitely proved *the universality of an elementary electric charge* and its importance for larger material bodies just as much as for separate atoms.

THE ELECTRON AS AN ELEMENTARY ELECTRIC PARTICLE

Thus far we have spoken of definite portions of electricity carried by atoms, by Millikan's oil droplets, or by still larger material bodies. But does the electric charge always stick to material bodies, and is it possible to sepa-

rate this charge from material carriers and study it separately in free space?

We have already seen that all bodies illuminated by ultraviolet light become positively charged. Since the light does not carry any electric charge, and thus cannot supply with positive electricity the bodies on which it falls, we must conclude that the observed effect is actually due to the loss of negative electricity by the illuminated surfaces of material bodies, a phenomenon similar to that of the so-called *thermionic emission,* that is, the emission of negative charges by the surfaces of hot bodies. Moreover, since all bodies consist of separate atoms, it becomes evident that the effect of illumination or heating is to extract and throw out elementary electric charges of separate atoms, and we come to the conclusion that these particles of negative electricity are comparatively loosely bound constituent parts of atoms. These free negative charges are usually called *electrons,* and their discovery represents the first step toward the understanding of atomic structure.

THE MASS OF AN ELECTRON

Do these free electric charges possess any ponderable mass, and, if so, how large is it as compared with the mass of an atom? The mass of an electron, or, rather, the ratio of its electric charge to its mass, was first measured at the very end of the last century by the British physicist Sir Joseph John Thomson. If we let a beam of electrons, obtained by photoelectric or thermionic emission, pass between the two plates of a condenser (Figure 9), the electrons will be attracted to the positive electrode and repelled by the negative one, thus causing the beam to bend downward toward the former. This deflection can be easily

observed by allowing the electronic beam to fall on a fluorescent screen placed behind the condenser. The electric force acting on an electron is proportional to its charge, but the effect of the force in producing the deviation from the original direction of motion is inversely proportional to the mass of the moving particle. Thus it is only the ratio

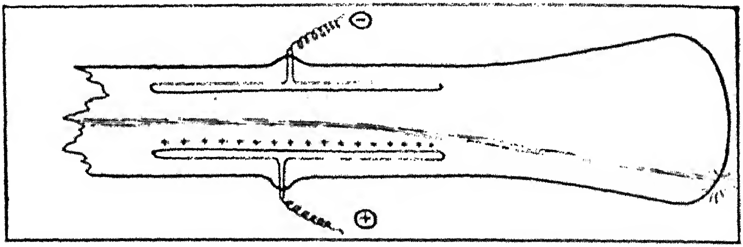


FIGURE 9
J. J. Thomson's arrangement for the measurement of the charge/mass ratio of electrons.

$\frac{\text{charge}}{\text{mass}}$, or the so-called *specific charge of the electron*, that can be derived from that kind of experiment.

But, in addition, the deflection also depends on the velocity of motion, and everyone knows that it is impossible to solve one equation with two unknown quantities. But it is not difficult to find another "equation" for our problem. If, instead of using an electric force, we use a magnetic one, produced by a magnet placed near the track of the electrons, the beam will also be deflected, but in a different way. Combining the results of these two experiments, we can calculate separately the values for the specific charge and for the velocity of electrons. From the values of the specific charge and of the known absolute charge, we get the mass of an electron, which turns out to be very

small indeed. *The mass of an electron is 1840 times smaller than the mass of a hydrogen atom.*

This does not mean, of course, that a hydrogen atom consists of 1840 electrons, for, in addition to the negatively charged electrons, the atom also contains positively charged parts, which are responsible for the main portion of the atomic mass.

THE ATOMIC MODEL

The question of the distribution of negative and positive charges within the atom was studied by one of the greatest physicists of our time, Sir Ernest Rutherford (later Lord Rutherford of Nelson), the father of modern nuclear physics, who in the year 1911 made the first sounding of the depths of an atom. His chief problem was to find a "sound" that would be small enough to be plunged into the minute body of an atom, and to locate its "soft parts" and its "skeleton," if there happened to be any.

To understand the method employed by Rutherford, imagine a hard-boiled customs officer of some little South American republic on the verge of revolution who must inspect a large shipment of cotton on the suspicion that inside the cotton bales there is hidden military contraband, but who has not the time to open and examine each pack separately. After some reflection, he draws his revolvers and opens fire on the pile of bales, sending bullet after bullet through the cotton. "If there is nothing but cotton inside these bales," he explains to the surprised bystanders, "my bullets will pass straight through or stick in the cotton. But if those damned revolutionists have hidden arms within that cotton, some of the bullets will ricochet and come out at unexpected angles."

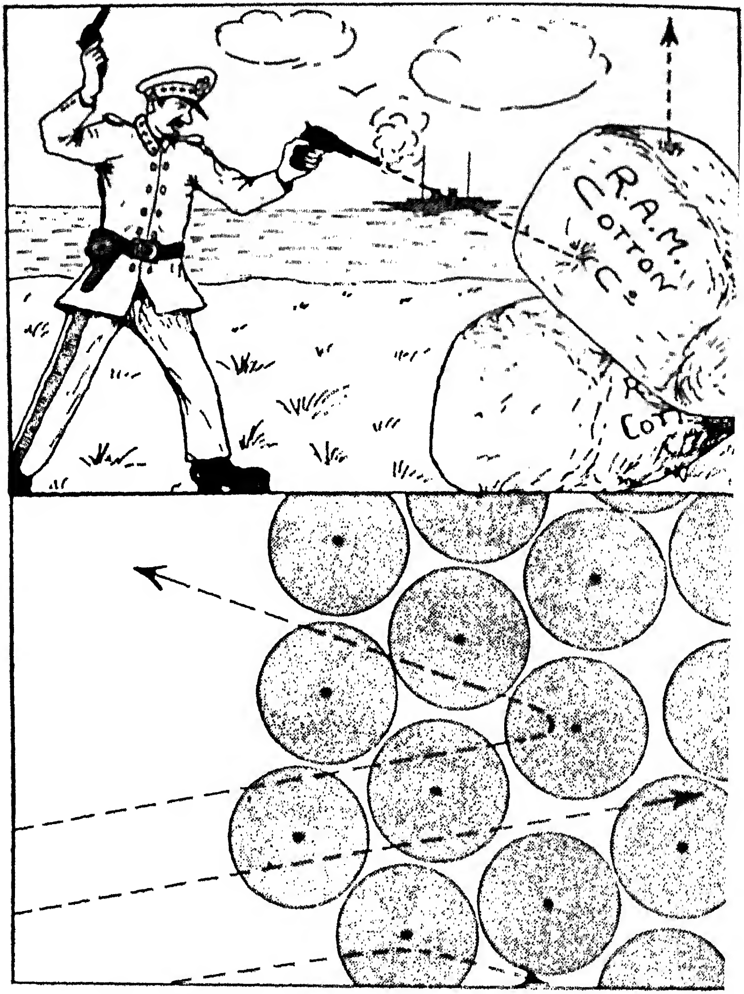


FIGURE 10
Detection of contraband in cotton bales, and of nuclei in atoms, by th ballistic method.

His solution is very simple and scientific and is essentially identical with the method applied by Rutherford (Figure 10), except that for tiny atoms the latter had to use correspondingly tiny projectiles. Rutherford bombarded his pile of atoms, that is, an ordinary piece of matter, with the so-called *α-particles,** which are the minute, positively charged projectiles emitted by some radioactive bodies. As it passes through the body of an atom, an α-particle will be influenced by the electric forces between its own charge and the charged parts of the atom, and must consequently deviate from its original direction of motion. Thus, by studying the scattering of a beam of α-particles that has passed through a thin foil of a given substance, one can form an idea of the distribution of electric charges within the atoms in question. If the positive and negative charges were distributed more or less uniformly through the body of the atom, no large scattering would be expected. If, on the contrary, there was a strong concentration of charge, let us say in the central parts of the atom, those α-particles which passed close to the centre would be strongly deflected, much in the same way that the bullets of our ingenious customs official rebounded from metallic objects hidden inside the cotton bales.

Rutherford's experiments actually showed very large scattering angles, indicating *a strong concentration of charge in the very centre of each atom*. Moreover, the character of the scattering showed that the charge concentrated at the centre had the *positive* sign. This central region (in which the positive charge of the atom and also the largest part of atomic mass are concentrated) is at least 10,000

* The rays involved in subatomic reactions are designated by the Greek letters *alpha* (α), *beta* (β), and *gamma* (γ). They will be described in the text below.

times smaller (in linear dimensions) than the whole atom. It has received the name of *atomic nucleus*. The negative charge surrounding this "point-skeleton" of each atom and constituting, so to speak, the "atomic flesh" must evidently consist of *a number of electrons revolving around the central nucleus under the forces of mutual electric attraction* (Figure 11). Owing to the comparatively small mass of

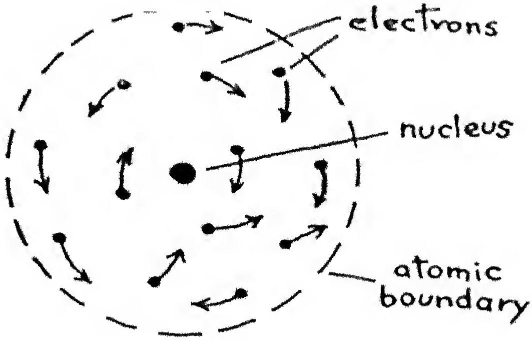


FIGURE 11
Rutherford's model of the atom.

electrons, this "negative atomic atmosphere" practically does not influence the motion of the heavy α particles passing through the body of the atom, any more than a swarm of mosquitoes could influence a frightened elephant rushing through the jungle. Only those α-particles that are aimed directly, or almost directly, at atomic nuclei will deviate sharply from their original track and, in some cases, even bounce directly backward.

ATOMIC NUMBER AND THE SEQUENCE OF ELEMENTS

Since the atom as a whole is electrically neutral, the number of negative electrons revolving around its nucleus

must be determined by the number of elementary positive charges carried by the nucleus itself, which, in its turn, can be directly calculated from the study of the scattering angles of α-particles that have been deflected by the nucleus. It was thus found that *the atoms of the various elements differ among themselves in the number of electrons revolving around their nuclei.* The atom of hydrogen has one electron, that of helium two, and so on up to the heaviest known element, uranium, the atoms of which contain ninety-two electrons each.

This numerical characteristic is generally known as the *atomic number* of the element in question, and it coincides with its positional number in the sequence in which the elements had already been arranged according to their chemical properties.* We see then that *all the physical and chemical properties of any given element can be characterized simply by one number giving the positive charge of its atomic nucleus or, what is the same thing, the normal number of its atomic electrons.*

ISOTOPES

But more recent research, due mostly to the British physicist F. W. Aston, has indicated that, although the charge of the atomic nucleus is well defined for any given chemical element, its mass may be different in different cases. It was shown, for example, that *ordinary chlorine is actually a mixture of two kinds of atoms, each with the same number of electrons but with different nuclear masses.* Three-quarters of the mixture consists of chlorine atoms with the mass 35 (relative to hydrogen), and one-quarter consists of those with the mass 37. The average atomic

* See Figure 12 below, pp. 46–47.

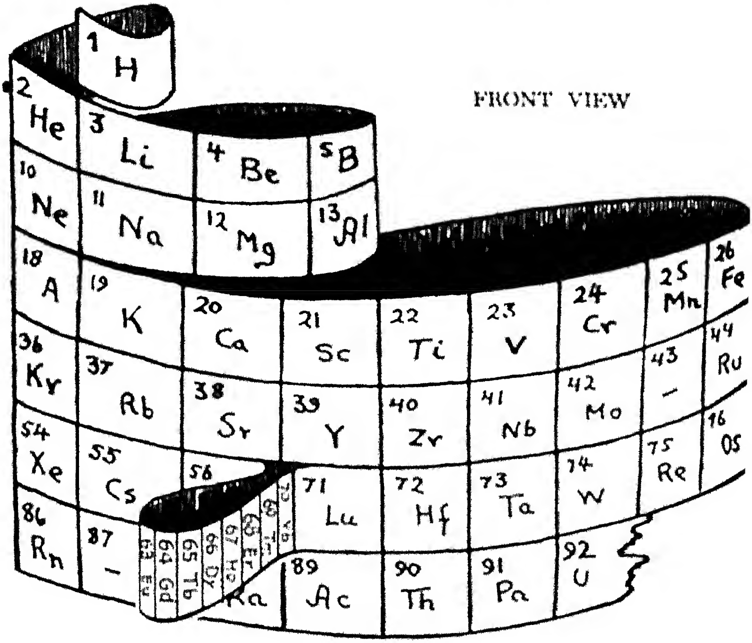
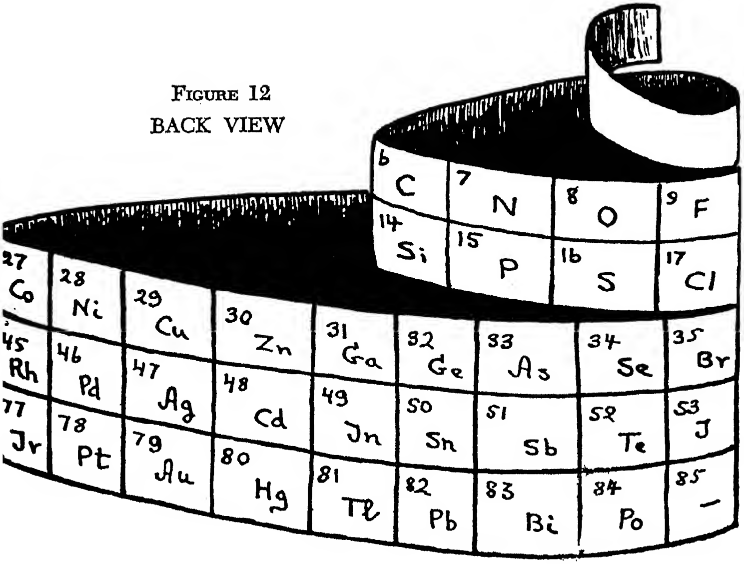


FIGURE 12
The periodic system of elements on a cylindrical band, showing the periods of 2, 8, and 18. The loop in the sixth period corresponds to the elements (rare earths) which fall out from regular periodicity owing to the reconstruction of atomic shells.

weight of the mixture comes out to be $(35 \times \frac{3}{4}) + (37 \times \frac{1}{4}) = 35.5$, which is in good agreement with the previous chemical estimates of the atomic weight of chlorine (35.46).

Atoms that are identical in their number of electrons and in all ordinary chemical and physical properties, but differ in their mass, have received the name of *isotopes* (i.e., "occupying the same place" in the natural sequence of elements). At the present time we have several good

Figure 12
BACK VIEW



methods for separating isotopes from each other, so that we can now have, for instance, two chlorines, with exactly the same chemical properties but having different atomic weights.

The researches of Aston and others have led to the conclusion that most of the chemical elements as we know them represent a mixture of two or more isotopes. In atmospheric air, for example, consisting mostly of nitrogen with the mass 14 and oxygen with the mass 16, there is also a small admixture of the heavier isotopes of these elements (0.3 percent of nitrogen 15, and 0.03 percent of oxygen 17).

One of the most interesting findings of recent times is the discovery and isolation of *the heavy isotope of hydrogen* (or *deuterium*) by the American chemist H. C. Urey.

The water in the molecules of which ordinary hydrogen atoms are replaced by their heavier isotopes (*heavy water*) is about 5 percent heavier than ordinary water, and would represent a great advantage for poor swimmers. But heavy hydrogen presents other, much more valuable features; we shall see later that its use in the field of nuclear physics leads to very important information concerning the structure of the atomic nucleus and the processes of the artificial transmutation of elements.

THE SHELL STRUCTURE OF AN ATOM

It was first indicated by the Russian chemist Dmitri Mendelyeev that, in the series of elements arranged according to their increasing atomic weights, all physical and chemical properties repeat themselves with a rather regular periodicity. This can easily be seen from Figure 12, where the elements are arranged in a cylinder in such a way that those with analogous properties are situated above each other.*

The first period contains only two elements, hydrogen and helium; then we have two periods of eight elements each; and finally the properties repeat themselves after every eighteen elements. If we remember that each step horizontally along the sequence of elements corresponds to the addition of one more electron, we must inevitably conclude that the observed periodicity must be due to *the recurrent formation of certain stable configurations of atomic electrons, or "electronic shells."* The first stable shell must consist of only two electrons, the next two shells

* It is to be remembered that the diagram represents a cylinder, in which helium, for example, is midway between hydrogen and lithium. Helium, therefore, and the column of elements below it, might just as correctly have been placed at the extreme right of the "back view."

of eight electrons each, and all the following shells of eighteen electrons each.*

In Figure 13 we give the schematic pictures of three different atoms, one with a completed and two with uncompleted shells.

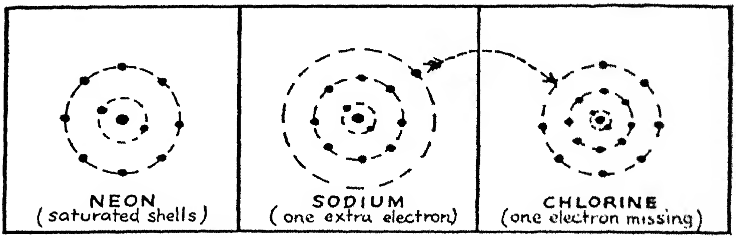


FIGURE 13
Shells in different atoms.

CHEMICAL BINDING

We can now answer the question concerning the forces that give rise to the formation of complex molecules from the separate atoms of different elements. From Figure 13 we see, for example, that the atom of chlorine is short only one electron of having a completed outer shell. On the other hand, the atom of sodium has one electron left over after the formation of a completed shell. Thus, we should expect that, when atoms of these two elements meet, the extra electron of the sodium atom will go over to complete the shell of the atom of chlorine. As the result of such an exchange, the sodium atom will become positively charged (by losing a negative charge), while the atom of chlorine will become negatively charged. Under the action of the forces of electric attraction, the two atoms will therefore

* Note that toward the end of the sequence the strict periodicity of properties is somewhat confused. This is due to the beginning of the internal reconstruction of some previously completed inside shells.

cleave together, forming a molecule of sodium chloride, or ordinary table salt.

In the same way an atom of oxygen, which lacks two electrons to complete its shell, will "rob" two hydrogen atoms of their single electrons, thus forming a molecule of water (H_2O). On the other hand, there will be no tendency to combine as between the atoms of oxygen and those of chlorine (both "electron-lacking") or as between the atoms of hydrogen and those of sodium (both "glad to get rid of their extra electrons"). In the case of atoms with completed outer shells (helium, neon), there will be neither give nor take, and these elements therefore remain chemically inert.

From this picture of chemical reactions we may also conclude that the energy liberated in the process of the formation of a molecule must be given by the differences in the electronic bindings in the two or more atoms entering into the reaction. As the potential energy between the electron and the nucleus of an atom is of the order of magnitude of 10^{-12} ergs, this must also be the order of magnitude of the energy liberated per atom in various chemical reactions.

THE CLASSICAL THEORY FAILS IN THE ATOM!

We come now to a critical point in the development of the atomic theory. The reader may already have noticed that Rutherford's model of an atom (Figure 11), consisting of a small and heavy central nucleus with a number of electrons revolving around it under the action of mutual electric attraction, is analogous to the system of planets revolving around the Sun under the action of the forces of gravity. The analogy seems still further emphasized by the fact that both electric and gravitational forces vary in

inverse proportion to the square of the distance and thus must both lead to the same type of elliptic orbit.

But there is one important difference that should not be overlooked in this comparison. Electrons, revolving around the nucleus in an atom, carry a relatively large electric charge and thus are bound to emit electromagnetic waves, much as do the antennæ of a radio-broadcasting station. But since these "atomic antennæ" are so much smaller, the electromagnetic waves emitted by atoms are billions of times shorter than those of a standard broadcast. Such short waves are perceived by the retina of our eye as the phenomenon of light, and their emission by the atoms of any given body make this body luminous. We are therefore obliged to conclude that the electrons revolving around the nucleus in Rutherford's model must be emitting light waves and, as a consequence of this emission, steadily losing their kinetic energy. It is easy to calculate that, if this were true, all atomic electrons would completely lose their kinetic energy in a negligibly small fraction of a second and fall down on the surface of the nucleus.

And yet very good experimental evidence has shown that such a collapse does not take place, and that the atomic electrons are perpetually moving around the nucleus, remaining all the while at a comparatively large distance from it. Besides this contradiction as to the fundamental nature of the atom itself, there appeared also a large number of other important discrepancies between theoretical predictions and experimental evidence. We have, for example, experiments showing that the light emitted by atoms consists of a number of well-defined wave lengths (line spectra), whereas the motion of electrons in

Rutherford's model should lead to the emission of a continuous spectrum containing waves of all possible lengths.

Practically none of the predictions of the classical theory was verified in the interior of the atom!

QUANTUM LAWS

These contradictions were troubling the mind of the young physicist Niels Bohr when he came from the green-roofed city of Copenhagen to work with Rutherford on the problems of atomic structure. It was clear to him that the situation was too serious to be solved by some minute modifications of the theory; everything indicated that the internal structure of the atom was the rock upon which the glorious frigate of classical theory was doomed to be wrecked.

For if the motions taking place in the interior of an atom cannot be described by means of classical mechanics, it is the fault of classical mechanics and not of the atom. After all, there were no *a priori* reasons, apart from those of tradition, why one should expect the system of classical mechanics, as created by Galileo and Newton for dealing with stars and massive bodies, to remain correct in its application to the "moving parts" of the tiny atomic mechanism. And so Bohr set out to deprive the classical system of mechanics of its rank as absolute and universal theory, which it had proudly claimed for centuries, and to look for a new, more general theory of motion, in respect to which the classical mechanics should be considered as only a special case.

Following the German physicist Max Planck, who in the year 1900 had put forward the revolutionary hypothesis that *the emission and absorption of light can take place*

only in the form of certain discrete portions, or quanta, of energy, Bohr accepted also the principle that *the mechanical energy of any moving system of particles must be "quantized," that is, it may take on only one of a certain set of discrete values.* This concept of the discontinuity of energy (which is, of course, quite outside the scope of the classical theory) may be considered to be in a certain sense a statement of the *atomicity of energy*—with the exception, of course, that in this case there is no universal elementary portion (such as, for example, the electron in the case of electricity), the size of the energy quantum being defined in each particular case by various additional conditions. Thus, in the case of radiation, *the energy of each separate light quantum is inversely proportional to the wave length of the light,* whereas in the case of a system of moving particles *the quantum of mechanical energy increases with the decreasing dimensions of the system and also with the decreasing mass of the particles.*

We see now that in the case of radiation the energy portions, or quanta, though negligibly small and unimportant for the long waves of radio broadcasting, become of great significance for the much shorter light waves emitted by atoms. Similarly the quantum of mechanical energy comes into importance only for systems of such small size as that of electrons revolving around an atomic nucleus. And, whereas in ordinary life we can easily disregard the atomicity of energy, just as we disregard the atomicity of matter, in the microcosm of atoms the situation becomes entirely different. The electrons in Rutherford's model do not collapse on the nucleus *simply because they possess the minimum amount of energy that such particles can possess under such conditions.* Since they do possess this minimum

of energy, which cannot on principle be decreased any further, their motion may be described as the "zero-point motion," which in classical physics would correspond to complete rest.

If we seek to give some additional energy to the atom, the first quantum of it completely changes the atom's state of motion and brings its electrons into the so-called *first excited quantum-state*. In order to return to the normal state, our atom has to emit the previously obtained amount of energy in the form of a single light quantum, which accounts for the well-defined wave length of the emitted light.

THE NEW MECHANICS

In spite of the fact that Bohr's theory of the atom made for tremendous progress in our understanding of subatomic phenomena, it is clear that it did not yet represent a final form for a consistent theory of subatomic motion. Another startling development of the quantum theory followed in the year 1926, when the Austrian physicist Erwin Schrödinger and the German physicist Werner Heisenberg, simultaneously and independently of each other, proposed what is now known as *the new system of mechanics.*

Schrödinger based his theory on the ingenious idea of the brilliant Frenchman Louis de Broglie, according to whom any motion of a material body is accompanied and guided by some special material "pilot waves," which give to any such motion certain properties that are characteristic only of wave phenomena. Heisenberg's theory of the new mechanics was based upon a seemingly entirely different idea, according to which the position and velocity of any moving particle have to be described, not by ordinary num-

bers, but rather by certain *noncommutable matrices*, which have been known in pure mathematics for more than a century. In spite of these apparently profound differences, however, it was soon shown that the two theories were mathematically equivalent and represented only different approaches to the same physical reality.

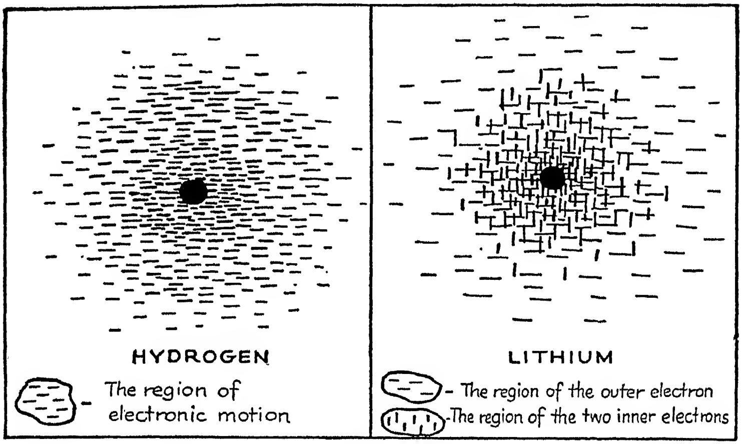


FIGURE 14
Wave-mechanical picture of atoms.

This reality was revealed soon afterwards by the penetrating criticisms of the classical ideas of measurement made by Heisenberg and especially by Bohr. It was shown that the existence of quantum phenomena makes necessary the introduction into the description of the physical world of a certain *uncertainty principle,* in contrast with the strict causality and determinacy of the classical theory. According to this principle of indeterminacy, the most fundamental notions of classical mechanics—such as, for example, the notion of the trajectory—must be completely

rejected in this new mechanics, and the motion of an electron around the atomic nucleus is to be represented, not by a well-defined orbit, but rather by a continuous "spread-out" picture, as shown in Figure 14.*

More detailed discussion of the principles of the new mechanics is, however, outside the scope of this book, and the reader who is interested in the problems of indeterminacy in modern physics is advised to turn to the special books on that subject.†

THE PROBLEM OF THE ATOMIC NUCLEUS

We have seen in this chapter how the atom, introduced into science more than 2000 years ago as the smallest possible and logically indivisible portion of matter, turned out to be, in the light of modern physics, a rather complicated mechanical system. If anything was left of the Democritean ideas of indivisibility and permanence, these attributes were now moved deeper into the atomic interior and ascribed to the nucleus, which, according to Rutherford's model, ought to be a dead, motionless centre of rotation for the atomic electrons.

The phenomena of radioactivity, which are to be described in the next chapter, will show, however, that even this, at first sight dead and inactive, "atomic skeleton" possesses a very definite internal structure, a structure that is probably even more complicated than that of the atom itself.

* This is why it was impossible to determine precisely the geometrical dimensions of an atom or molecule (see p. 30 above).

† A popular discussion of the new mechanics and of the principle of indeterminacy in physics may be found, for example, in the author's *Mr. Tompkins in Wonderland* (New York, Macmillan, 1940). It should be emphasized, however, that a knowledge of quantum mechanics is not necessary to an understanding of the rest of the book.

The Transmutation of Elements

THE DISCOVERY OF RADIOACTIVITY

THE discovery of radioactivity was due more or less to pure accident, though, if this accident had not happened as it did to Professor Becquerel, the leakage of energy from the interior of slowly decaying atomic nuclei would surely have been noticed anyway in some other connexion. Henri Becquerel, professor of physics at the Sorbonne, was interested in the phenomena of *fluorescence,* which is the property certain substances have of accumulating the energy of light falling upon them and of remaining luminous for a certain time after the source of light has been removed. Once during the year 1896 Becquerel obtained a preparation of uranium bisulphate for the purpose of studying the phosphorescence of this substance. But his interests were drawn in some other direction, and he threw the material into one of the drawers of his work-table.

Now it happened that in this drawer was a box containing some unexposed photographic plates, and the ampoule of uranium bisulphate fell right on top of that box, remaining there undisturbed for several weeks. Intending to take some photographs (whether a family portrait or some complicated absorption spectrum we do not know), Becquerel finally opened the drawer, pushed aside the ampoule with the forgotten preparation, and took out

the box with the plates. But when he developed his photographs he found that the plates were badly spoiled, as if they had been previously exposed to light. This was very strange, since the plates had been carefully wrapped in thick black paper and never yet opened. The only object in the drawer that might have been responsible for the damage was the preparation of uranium bisulphate, which had for so long rested so close to the plates.

Is it possible, thought Becquerel, turning over in his hands the ampoule with the suspected material, that this substance, spontaneously and without any previous excitation, emits some invisible, highly penetrating radiation that can pass without difficulty through the cover of the box and the black paper and affect the photographic emulsion? To answer this question, he repeated the experiment with some new plates. But this time he deliberately placed an iron key from one of the drawers between the photographic plate and the hypothetical source of the mysterious radiation.

A few days later, Becquerel's hands were probably shaking with excitement as, under the red lamp of the photographic darkroom, a diffuse silhouette of the key began to appear slowly against the darkening background of the negative. Yes, it definitely was *a new kind of radiation coming from the atoms of uranium,* a radiation that easily penetrated materials nontransparent to ordinary light but was still unable to pass through the thickness of an iron key!

Subsequent investigations have shown that the only other element known at that time capable of the same type of spontaneous radiation was *thorium,* the heaviest element after uranium; but the laborious search undertaken by a

scientific French couple, the Curies, soon led to the discovery of entirely new radioactive elements. After about two years of hard work Madame Curie finally succeeded in extracting from some uranium ores (pitchblende from Bohemia) two previously unknown elements with considerably higher radioactivity than either uranium or thorium; one of them was called *radium* and the other *polonium,* in honour of Madame Curie's native country. Still later, another radioactive element, called *actinium,* was discovered by one of the collaborators of the Curies; and it was also shown that the preparations of radium give rise to a strongly active gaseous substance, which received the name of *emanation of radium* or *radon.*

The growing number of new radioactive elements rapidly filled the hitherto blank spaces in the last line of the periodic system, and the fact that all these radioactive elements were grouped at the very end of the natural sequence of elements strongly suggested that their peculiar activity must in some way be connected with the increasing complexity of their atoms.

THE DECAY OF VERY HEAVY ATOMS

In the year 1903, the British physicist Ernest Rutherford, whose name we have already encountered in connexion with the nuclear model of the atom, advanced the hypothesis that *the atoms of very heavy elements are inherently unstable, and decay slowly with the emission of their constituent parts.* He showed, indeed, that the so-called *α-rays* emitted by radioactive substances are actually beams of very fast-moving, positively charged nuclei of the element helium. (It was with these α-particles, it will be remembered, that Rutherford bombarded his atoms.) After it has

lost its original high energy by collisions with the atoms of the matter through which it has passed, the α-particle slows down and, by capturing two free electrons for its orbit, forms an ordinary atom of helium. Helium, as a matter of fact, can always be detected in old radium. Since α-particles are evidently ejected from the interior of the atomic nuclei of radioactive elements, we say that such nuclei are unstable; after losing one or more α-particles (i.e., four units of mass and two charges per particle), the nucleus of a radioactive atom is transformed into the nucleus of a comparatively lighter element occupying a less advanced position in the periodic system.

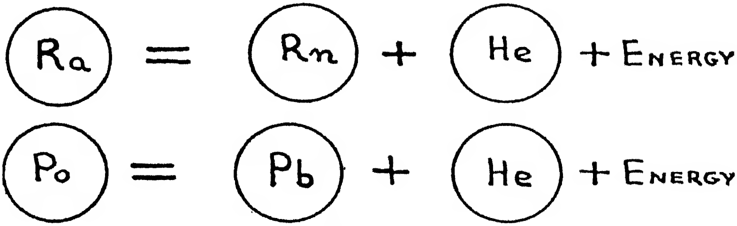


Figure 15
Spontaneous disintegration of unstable nuclei: (1) radium into radon and helium; (2) polonium into lead and helium.

For example, the α-emission of radium ($Z = 88$, $A = 226$)* transforms it into the emanation, or radon ($Z = 86$, $A = 222$); and an α-particle escaping from the polonium nucleus ($Z = 84$, $A = 210$) leaves behind it an atom of lead ($Z = 82$, $A = 206$). These two disintegration reactions may be written formally in the manner shown in Figure 15. With lead, the sequence of successive α-transformations comes to a stop because lead already belongs to the region

* $Z =$ the numerical position occupied by an element in the periodic table (see Figure 12); $A =$ the atomic weight of the element relative to hydrogen ($= 1$).

of elements with stable nuclei and no decay beyond this point is possible.

The progressive disintegration of heavy unstable elements is from time to time, however, interrupted by the emission of a negative electron coming apparently from inside the decaying nucleus. This electronic emission from the nucleus, known as *β-ray emission,* without changing

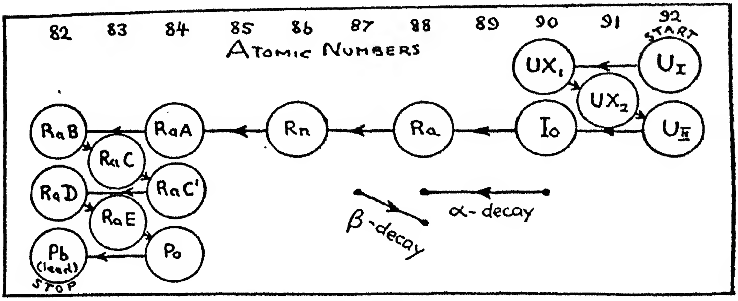


Figure 16
Decay in the uranium family. The arrows indicate the successive changes of position in the periodic table due to α- and β-transformations. The encircled letters are the chemical symbols of different radioactive elements, e.g., U, uranium; Io, ionium; Ra, radium; Rn, radon; Po, polonium.

the actual mass of the atom (since the insignificant mass of the electron may be disregarded), increases its atomic number, moving the corresponding element one step forward in the periodic table.* But this temporary advance is soon overcompensated by the following series of α-emissions, and the unstable element, moving sometimes two steps backward and sometimes one step forward, slowly retreats from the unstable region until it finally arrives at an impregnable position, having been transformed into lead.

* The loss of a negative electric charge is evidently equivalent to the increase of the total positive charge of the nucleus. See also p. 65 below.

Such sequences of successive nuclear transformation are known as *radioactive families;* and we have the *uranium family* (Figure 16), containing radium as one of its members, the *thorium family,* and *the family of actinium.*

Finally, the processes of α-particle and β-ray ejection are often accompanied by a strong internal excitation of the decaying nucleus, leading to the emission of extremely short-wave electromagnetic radiation, analogous to ordinary X-rays and generally known under the name of γ-*rays.* This highly penetrating radiation (unlike α- and β-radiation, it is not composed of material particles) is in many cases responsible for the photographic and other effects produced by radioactive substances.

LIBERATED ENERGY AND DECAY PERIODS

It has already been intimated—as when we saw Rutherford use them for projectiles—that the kinetic energies of α-particles emitted in the process of spontaneous nuclear disintegration reach extremely high values. The α-particles are emitted from radium, for example, with a velocity of 1,500,000,000 centimetres (9000 miles) per second, surpassing the ordinary velocities of thermal motion at room temperature by a factor of thousands; and, in spite of their small mass, they possess an energy of 0.000,007 erg per particle. Thus, the concentration of energy in α-particles (the energy calculated per unit mass) is actually a billion times greater than the corresponding concentration in the shells used in modern artillery.

If all the atoms contained in a gramme of radium should emit their α-particles almost simultaneously, let us say within an hour, the tremendous energy of 2×10^{16} ergs would be liberated. Thus the subatomic energy contained

in several pounds of radium would be sufficient to drive a big transatlantic liner to Europe and back, or to run an automobile motor continuously for several hundred years. However, the subatomic energy hidden in the interior of radium nuclei is not liberated in a single outburst but rather leaks out of them at a very slow rate. In fact, it takes 1600 years for one-half of a given number of radium atoms to disintegrate and another 1600 years for the remaining half to be halved again. This slowness of radioactive decay makes the energy liberation per unit time comparatively low; and in order to warm up a cup of tea by the energy leaking from one gramme of radium (priced at $40,000) we should have to wait several weeks.

In the case of uranium and thorium, with decay periods of 4.5 and 16 billions of years respectively, the rate of energy liberation is correspondingly still smaller. There are also short-lived elements, such as radon (with a life period of 3.8 days) or RaC′ (disintegrating in 0.000,01 second); but, precisely because of their rapid disintegration, their presence in radioactive minerals is so minute that it cannot be even detected by the ordinary chemical methods.

We shall see later (Chapter XII) that all the radioactive elements at present known have actually been formed in the very early stages of the development of the universe, and in this sense represent the "earliest documents of creation." Only those of them, such as uranium and thorium, that possess lifetimes comparable with the present age of the universe (about two billions of years) can still be found at present, together with their various disintegration products (the members of their corresponding families). If unstable elements of even higher atomic number were created at this early epoch, when the formation of elements took

place, they must have been completely disintegrated during the intervening billions of years and left no trace on our planet.

THE "LEAKING OUT" THEORY OF RADIOACTIVE α-DECAY

If the nuclei of radioactive elements are unstable, and can decay by the emission of their constituent parts, what prevents them from doing so all at once? Why do the nuclei of uranium and thorium retain their α-particles for billions of years, whereas other nuclei eject their α-particles within a small fraction of a second? These questions, which were for a long time the heart of the great puzzle of the theory of radioactivity, insistently returned to the mind of the author of this book while he was visiting the University of Göttingen during the summer of 1928. Göttingen was a dull little town whose total of entertainment possibilities was represented by two poor movie theatres; and the author, who had hoped for something more on his first trip abroad, had nothing better to do than to take up research.

It was clear to him that the escape of α-particles through the "high potential walls" surrounding their nuclear dungeon must be quite impossible from the point of view of classical physics; for, according to the experiments of Rutherford, which had just been published at that time, the "walls" surrounding radioactive nuclei were of an energy much higher than that of the α-particles. But, although in the frame of classical theory radioactive decay seemed to be made absolutely incredible, the new quantum mechanics offered a possible means for explaining the process. Thinking in this direction, the author was soon able to prove that *the decay of the radioactive elements is*

really a purely quantum-mechanical process in which α-particles "leak through" the nuclear potential walls, just as an old-fashioned ghost passes through the thick walls of an ancient castle. The quantum-mechanical formula obtained for *the "transparency" of the nuclear walls* proved to be in excellent agreement with the observed relation between the energy of emitted particles and the corresponding decay periods, leaving no doubt that the proposed explanation was correct.

Practically at the same time that the author was developing this theory of α-decay in the old German town, a very similar explanation of radioactive phenomena emerged from the discussion between two other physicists, R. W. Gurney and E. U. Condon, on the other side of the Atlantic.

In the years that followed, the quantum theory of nuclear potential walls turned out to be very useful, not only for the understanding of the processes of spontaneous α-decay, but also in its various applications to the problems of the artificial transformations of elements caused by nuclear bombardment. It was useful also in describing the thermonuclear reactions which, as we shall see later, represent the main source of stellar energy.

THE PROCESS OF β-DECAY AS AN ELECTRIC ADJUSTMENT OF THE NUCLEUS

We have mentioned above (p. 60) that the sequence of successive α-emissions in any radioactive family is from time to time interrupted by the emission from the nuclei of free negative electric charges, or electrons. Thus it would be natural to suppose that electrons, along with α-particles, represent substantial constituent parts of atomic nuclei. Closer study of this question, into which we cannot enter

here, has, however, led physicists to the conclusion that electrons, as such, do not actually exist inside the nuclei. For one thing, the size of electrons seems to be too large to admit of many of them being squeezed into the tiny volume of the nucleus.

This conclusion, at first sight paradoxical, is resolved in the current point of view, according to which *the electrons emitted by certain radioactive bodies are "created," just before their emission, out of the "shapeless" electric charge carried by the nucleus.* It is admittedly rather difficult to explain this point of view without going into much technical detail; and we shall content ourselves with the proposition that *electrons do not exist inside the nuclei before they are emitted,* just as soap-bubbles do not exist inside a pipe before they are blown out.

Whenever a sequence of α-emissions disturbs the delicate balance between the electric charge and the mass of the decaying nucleus, an electric adjustment immediately takes place, and the superfluous charge is emitted in the form of a free electric particle. We may take as an example what happens when one of the members of the radioactive family of thorium, known as ThC, ejects a very energetic α-particle. The nucleus of ThC is thereby transformed into the nucleus of ThC″, which possesses the atomic weight 208 and the positive charge of 81 elementary units. If, however, we look into the table of stable elements, we will find that the stable nucleus of mass 208 should possess an electric charge of 82 units, since it is an isotope of lead. It follows that, in order to become stable, the product of ThC disintegration must emit one free negative charge (a β-particle), upon which it will become transformed into ordinary lead and will thus exist for ever after.

We shall see later that the nuclei formed in the processes of so-called artificial nuclear transformation may sometimes have their electric balance restored in the opposite direction, stabilizing themselves by emitting a free *positive* charge. For instance, the artificially produced nuclei of nitrogen, with atomic weight 13 (light isotope), transform themselves into stable carbon nuclei (the heavy isotope, also of atomic weight 13) by such an emission. The discovery of these hitherto unknown *positive electrons,* the existence of which was predicted theoretically by P. A. M. Dirac, opened up a new epoch in the progress of our knowledge of the properties of β-decay, but the discussion of this falls outside the scope of the present book.

BACK TO ALCHEMY

The discovery of decaying radioactive elements showed that the medieval alchemists had not been so far wrong after all in dreaming of the artificial transmutation of one element into another. If the internally unstable elements situated near the upper end of the natural sequence could be spontaneously transformed into one another, there was every reason to believe that in the case of the lighter, normally stable elements, too, such transformations might be artificially caused under sufficiently strong external influences.

The alchemists had failed ignominiously in the attempt, but the only influences they could bring to bear in their time were those of ordinary chemical and thermal reactions, whereas the binding energies within atomic nuclei exceed the ordinary chemical binding energies by a factor of millions. The alchemists' attack on the nucleus may be compared to an attempt to bombard the modern fortifica-

tions of the Maginot or Siegfried Lines with medieval catapults.

In order to crack the walls of the stronghold of the atomic nucleus, one must use projectiles with an energy comparable to that of the particles shot out by the nuclei themselves. Having at our disposal various radioactive elements that emit high-energy α-particles, we can perhaps turn the fire of these nuclear batteries against the walls of lighter, ordinarily stable nuclei in the hope that some of the α-particles, making direct hits, will penetrate the walls and produce the desired damage in their interiors.

It was with this thought in mind that that restless explorer of the atomic interior, Ernest Rutherford, had in 1919 directed a beam of fast α-particles, as they came from some radioactive body, against the atoms of nitrogen moving quietly in a gas-filled chamber—and had cracked them!

PHOTOGRAPHING NUCLEAR BOMBARDMENT

The process of nuclear bombardment and its demolishing results may actually be observed in the aerial photographs of the nuclear battlefield taken soon after Rutherford's discovery by one of his students, Patrick Blackett. One would think that the nuclear projectiles are too small and move too fast to be directly photographed, but in a certain sense this is not so, and as a matter of fact it is much easier to photograph the trajectories of these minute but destructive particles than the trajectories of shells from army cannons.

The apparatus used for such photographs is usually known as a *cloud-chamber,* or *Wilson chamber,* and its operation is based on the fact that fast-moving charged particles, such as α-particles, produce on their way through

the air, or through any other gas, a certain distortion in the atoms situated along their route. With their strong electric fields, these projectiles tear off one or more electrons from the atoms of gas that happen to be in their way, leaving behind a large number of ionized atoms. This state of affairs does not last very long, for very soon after the passage of the projectile the ionized atoms will catch back their electrons, returning to the normal state. But if the gas in which such ionization takes place is saturated with water vapour, tiny droplets will be formed on each of the ions (it is the property of water vapour that it tends to accumulate on ions, dust particles, etc.), producing a thin band of fog along the track of the projectile. In other words, the track of any charged particle moving through a gas thus becomes visible in the same way as does the track of a smoke-writing airplane.

From the technical point of view, the cloud-chamber is a very simple apparatus (see Figure 17), consisting essentially of a metallic cylinder (*A*) with a glass cover (*B*) containing a piston (*C*), which can be moved up and down by an arrangement not shown in the picture. The space between the glass cover and the surface of the piston is filled with ordinary atmospheric air (or any other gas, if so desired) containing a considerable amount of water vapour. If the piston is abruptly pulled down, immediately after some atomic projectiles have entered the chamber through the window (*E*),* the air above the piston will cool and the water vapour will begin to precipitate, in the form of thin bands of fog, along the tracks of the projectiles. These bands of fog, being illumined by a strong light through

* This window is usually covered by a thin layer of mica, through which fast atomic projectiles can pass with very little difficulty.

another side window (*D*), will stand out clearly against the blackened surface of the piston and can be observed visually or photographed by the camera (*F*), which is operated automatically by the action of the piston. This simple arrangement represents one of the most valuable apparatus

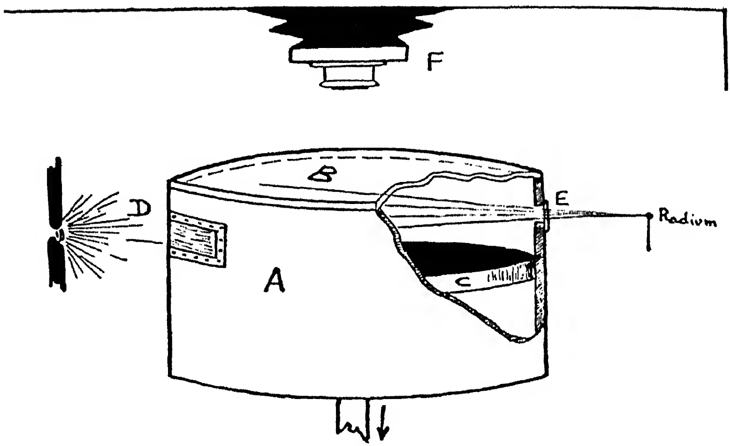


FIGURE 17
The scheme of Wilson's cloud-chamber.

of modern physics, and permits us to obtain beautiful photographs of the results of nuclear bombardment.

CRACKING THE NITROGEN ATOM

For the study of the bombardment of nitrogen atoms, Blackett needed to fill his chamber with nothing more than atmospheric air, which already consists largely of nitrogen. Of course, it is impossible to aim an α-particle through the side window directly at the nucleus of a nitrogen atom; one must simply count on the chance that,

with a sufficiently intense scattered fire of nuclear batteries, such a direct hit will occur once in a while.

On the first photographs taken with this arrangement no direct smashing hits were registered; the tracks of the α-particles passed straight through the chamber. But after taking a sufficiently large number of photographs—23,000 in fact—Blackett finally succeeded in obtaining eight that showed the head-on collisions of incident α-particles with the nuclei of nitrogen atoms. The observed extremely small chance of a smashing hit clearly indicated that, at this stage at least, the processes of nuclear transformation hardly represented any practical possibility either for the mass-production of new elements or for a large-scale source of subatomic energy.

One of the Blackett disintegration photographs is reproduced in Plate II, and a schematic representation of what actually happened during the collision is shown in Figure 18. This figure shows an α-particle approaching a nitrogen atom with great speed and making a head-on collision with its nucleus. We also see the results of this impact: a proton (i.e., a hydrogen nucleus) is ejected leftward from the nuclear interior, while the main body of the nucleus itself is shot at a rightward angle away from the site of the accident.* But the track of the α-particle itself has dis-

* It must be explained here that the cloud-chamber photographs not only give us the trajectories of participating particles, but also permit us to determine their nature. The amount of ionization produced by a moving particle depends on its electric charge, and the higher the charge, the thicker will be the band of fog formed in the cloud-chamber. We see from the photograph and Figure 18 that the left branch of the fork created by the collision is somewhat thinner than the track of the incident α-particle; this means that the particle that made the former track has a smaller charge than an α-particle and must consequently be a proton. On the other hand, the right branch of the fork is very thick, indicating a heavily charged nucleus.

appeared, from which we conclude that it must have stuck to the nucleus at the instant of collision.

The nucleus we observe as the product of the collision is therefore no longer a nucleus of nitrogen, but something

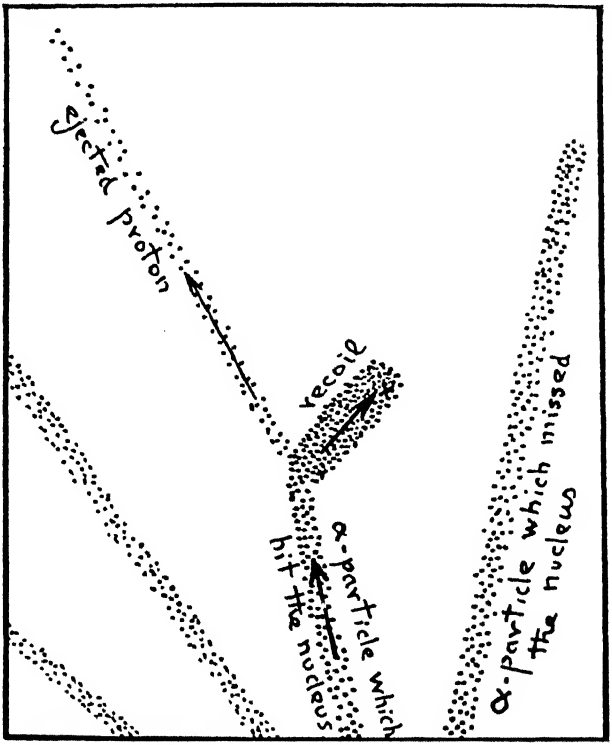


FIGURE 18
Analysis of Blackett's photograph of nuclear transformation given on Plate II (right). Separate points represent the drops of the fog.

quite different that has been formed by the addition to a nitrogen nucleus of an α-particle (a nucleus of helium) and the subtraction of a proton (a nucleus of hydrogen). This

operation causes an increase of nuclear charge by one unit ($+2-1$) and of nuclear mass by three units ($+4-1$); so that, instead of a nitrogen nucleus with atomic number 7 and atomic weight 14, we now have the nucleus of an oxygen atom with atomic number 8 and atomic weight 17. *Thus the α-bombardment of nitrogen atoms leads to their transformation into the atoms of oxygen,* and the old alchemic dream of the transmutation of elements is at last realized.

The processes of nuclear transformation can be formally represented (Figure 19) in a way very similar to the presen-

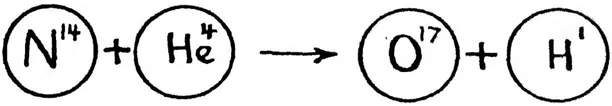


FIGURE 19
The collision between nitrogen and helium nuclei gives rise to the nuclei of oxygen and hydrogen. The superscripts represent atomic weights.

tation of ordinary chemical reactions between atoms, with the essential difference that we deal here with the processes going on within atoms themselves and not only with their position in molecules.

It should be noted also that the oxygen formed in the nuclear reaction described above possesses an atomic weight of 17 instead of 16, and therefore represents the heavy isotope of this element. We have already seen in Chapter II that atmospheric oxygen actually consists of two isotopes: the very abundant one O^{16} and a very rare one O^{17}, the latter present in a proportion of less than 0.03 percent.

Further experiments of Rutherford and his school have shown that many other light elements, when bombarded by fast α-particles, are subject to the same kind of nuclear

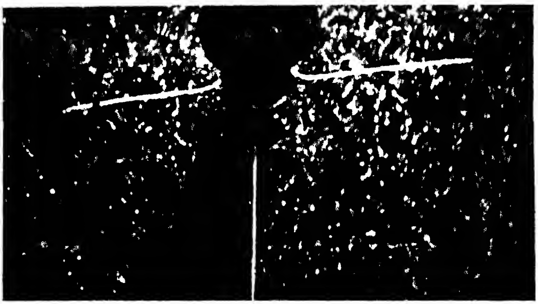
transformation as the one observed in the case of nitrogen. Thus, boron ($Z = 5$) was transformed into carbon ($Z = 6$), sodium ($Z = 11$) into magnesium ($Z = 12$), and aluminium ($Z = 13$) into silicon ($Z = 14$). *But the rate of these transformations, which is in any case very small, decreased rapidly with the increasing atomic weight of the bombarded element, so that no disintegration could be observed for any of the elements in the periodic system beyond argon.*

BOMBARDMENT BY PROTONS

In all the classical experiments on the artificial transformation of elements, α-particles were always used for the bombardment, since these were the only heavy projectiles spontaneously emitted by the nuclei of radioactive elements. The theory of nuclear transformation developed by the author of this book indicated, however, that a much higher efficiency could be expected if, instead of α-particles, fast protons could be used. Owing to the smaller electric charge of protons, they would suffer less repulsion in their approach to heavily charged nuclei, and would thus have a greater capacity for penetrating the nuclear interior. Besides, the use of new particles for nuclear bombardment could be expected to give rise to rather different types of nuclear reactions than those studied before.

But, since protons are not spontaneously emitted by ordinary radioactive elements, it was first necessary to produce artificially a high-energy beam of these particles by accelerating hydrogen atoms (or rather hydrogen ions) in very intense electric fields. The first successful experiments in this direction were carried out in Rutherford's laboratory in Cambridge by his young and gifted pupil J. Cockcroft. Using a high-tension transformer for 500,000 volts,

A. An artificially accelerated proton, emerging from the end of the ion tube of an atom-smasher, transforms a lithium nucleus into two α-particles. The cloud-tracks seen on the photograph correspond to these two α-particles flying in opposite directions. (See p. 75.)



B. An artificially accelerated proton splits a nucleus of boron into three α-particles flying in three different directions. (See p. 75.)

PLATE III. NUCLEAR DISINTEGRATIONS

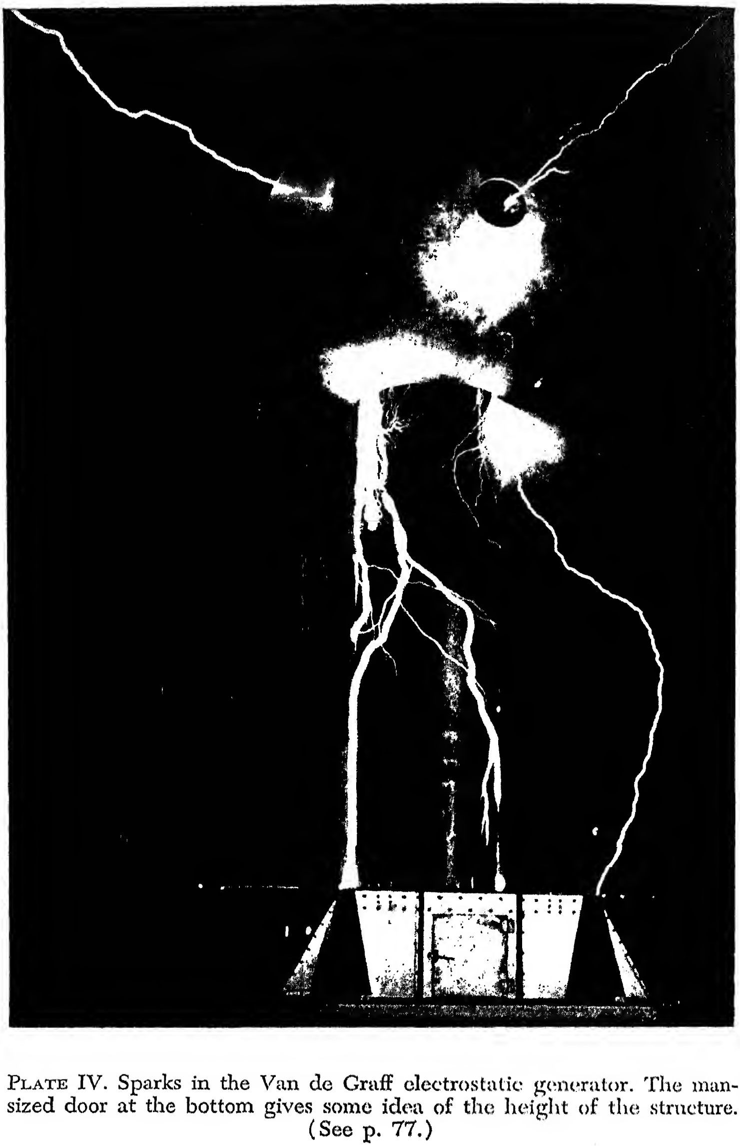


PLATE IV. Sparks in the Van de Graff electrostatic generator. The man-sized door at the bottom gives some idea of the height of the structure. (See p. 77.)

Cockcroft was able to produce a parallel beam of protons moving with the velocity of 10,000 kilometres per second. Although the kinetic energy of these artificially accelerated particles was still considerably smaller than the energy of the α-particles used by Rutherford, they turned out to be a quite efficient instrument for nuclear bombardment. Directing his beam at a target covered with a layer of lithium, Cockcroft noticed that many of the lithium nuclei, when hit by the incident protons, cracked and split into two equal parts (see Plate IIIA).

The equation of the nuclear reaction that took place in this case is shown in Figure 20, which makes it clear that

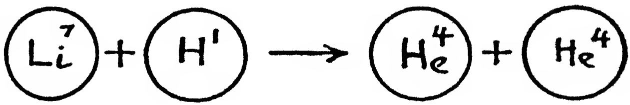


FIGURE 20
The collision between lithium and hydrogen nuclei gives rise to two helium nuclei (or α-particles).

the observed collision led to *the complete transformation of the colliding hydrogen and lithium nuclei into pure helium.* Among the other reactions that have been produced by proton bombardment we shall note here the transformation of nitrogen into carbon*:

$$ {}_7N^{14} + {}_1H^1 \longrightarrow {}_6C^{11} + {}_2He^4 $$

and the extremely interesting case (Plate IIIB) of boron,

* The numeral at the lower left-hand corner of each chemical symbol in these formulas represents the atomic number (Z) of that element; the upper right-hand numeral represents its atomic weight (A). Note that the Z's and A's are both balanced on either side of each "equation." In the first case the light isotope of carbon has been obtained, ordinary carbon being ${}_6C^{12}$.

which under the proton bombardment splits into three α-particles:

$$_5B^{11} + {}_1H^1 \longrightarrow {}_2He^4 + {}_2He^4 + {}_2He^4$$

As to the probability of the disintegrations produced by protons, it should be said that, while in general rather higher than that in the case of α-particle bombardment (in agreement with the theoretical prediction), it follows the same general laws, rapidly decreasing with the increasing weight of the bombardment element and the decreasing energy of the incident protons. However, some traces of the nuclear transformation of light elements have been observed for energies of incident protons as low as 10^{-8} erg.

The pioneering work of Cockcroft in the production of artificial beams of fast protons opened a period of great progress in the application of the high-tension technique to nuclear problems. At the present time many physical laboratories throughout the world are in possession of giant apparatus known under such diverse and curious names as *voltage-multipliers* (of the Cockcroft type), *electrostatic generators,* and *cyclotrons.*

THE ELECTROSTATIC "ATOM-SMASHER"

"Hey, Larry!" shouts Dr. Merle Tuve, sticking his head into a narrow opening of a giant steel sphere, sixty feet tall, erected on the grounds of the Carnegie Institution in Washington. "There's a telephone call for you!"

Suspended from the end of a rope high in the air, in the dim light of the cupola, Dr. L. Hafstad is carefully cleaning the surface of the sphere with an ordinary household vacuum cleaner. The surface of the sphere must be kept spotlessly clean and smooth, because any irregularity might produce an unwanted electric discharge. It was this neces-

sity that forced the usually kind-hearted Dr. Van de Graff, who was the first to build such a giant electrostatic generator in an abandoned dirigible hangar near New Bedford

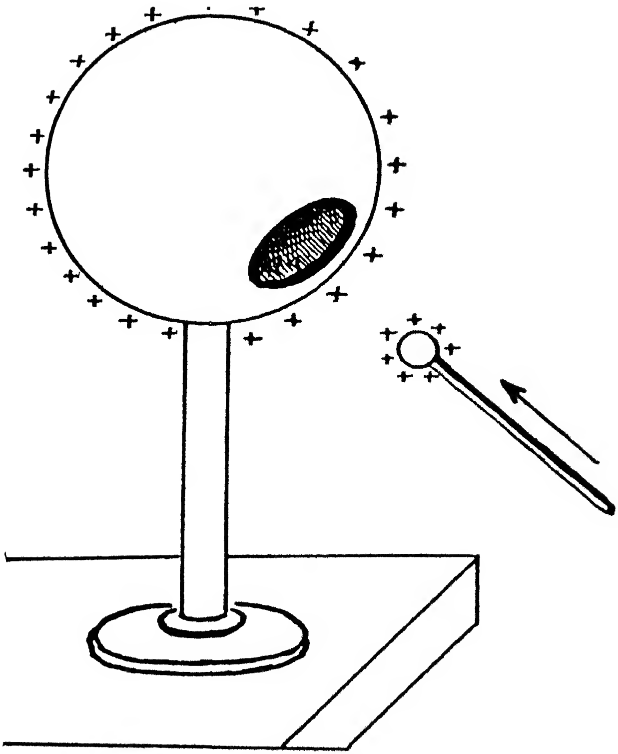


FIGURE 21
The principle of the electrostatic atom-smasher. A small spherical conductor charged with electricity gives its charge to a larger conductor if brought inside it through a hole.

(Plate IV), to shoot down several pigeons that lived under the roof of the hangar and were not sufficiently careful about the cleanliness of the sphere's surface.

While Dr. Hafstad is answering the phone call, let us inspect more carefully this giant atom-smasher. The reader will probably remember from his course in high school physics that an electric charge always tends to be distributed only over the surface of a charged conductor. This property of electricity is usually demonstrated in classrooms by introducing a small charged spherical conductor, mounted on a glass stick, into the hollow interior of a larger sphere and touching with it the inner surface of the latter (Figure 21). In this case, the electric charge from the small conductor goes over completely onto the outer surface of the larger sphere. By repeating this operation many times one can charge the larger sphere to arbitrarily determined high electric potentials, so that it will give off long sparks directed toward the nearest conducting objects.

In general, modern electrostatic generators differ from this simple arrangement only in size, but there are a great number of minute differences in elaborate detail. In particular, the transfer of the charge to the inside of the conductor is achieved not by the repeated introduction of a smaller charged body, but by a sort of conveyor system which supplies the charge continuously. An insulated circular belt runs between an electric transformer in the lower part of the structure, which provides the voltage, and a pulley fixed in the interior of the upper sphere; this belt steadily carries up electric charges and raises the potential of the sphere to a very high degree.

In the generator shown in Plate V, a potential of 5 million volts can be attained a few minutes after the belt starts carrying up its first electric charge. Although in principle there is no limit to the potential that can be obtained by this arrangement, in practice the limit is attained as

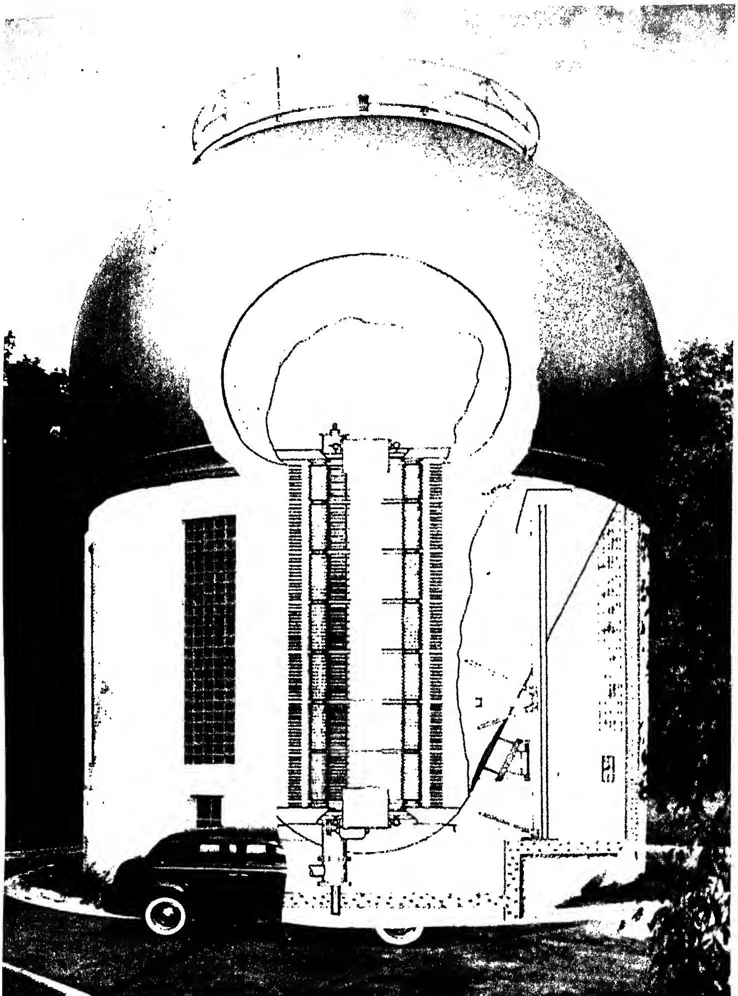


PLATE V. The electrostatic atom-smasher at the Carnegie Institution in Washington, D. C., which produces static electric tension up to 5 million volts. The cross-section shows the spherical conductor, its insulating supports, and the tube in which particles are accelerated. The charging belt is shown cut off near top and bottom. (See p. 78.)

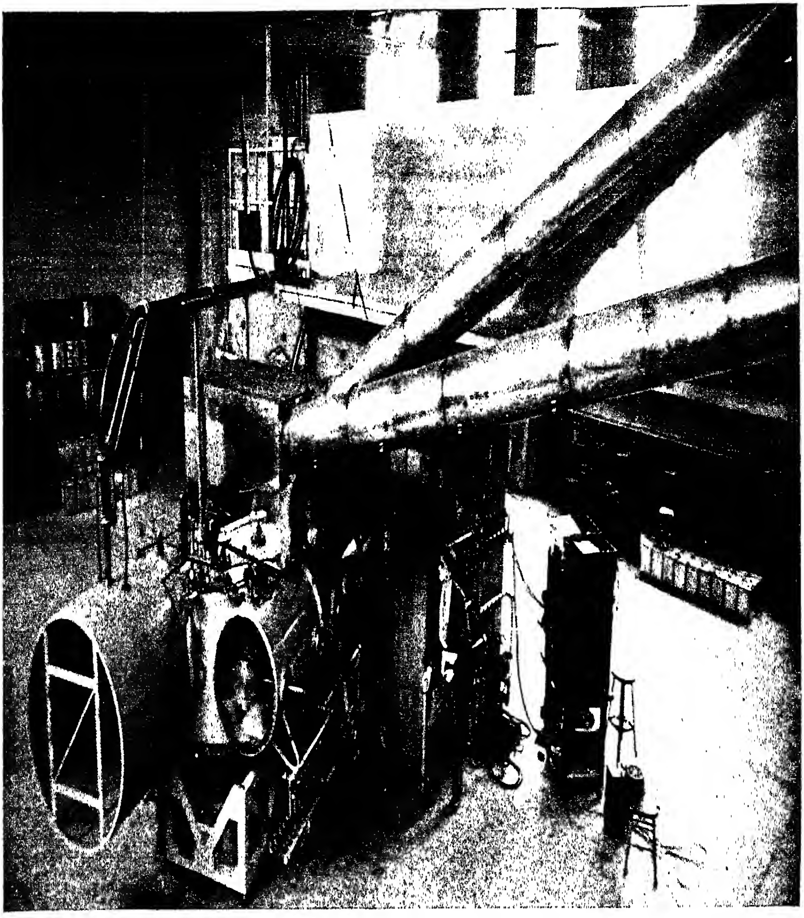


PLATE VI. The new Lawrence cyclotron in Berkeley, California, which produces α-particles with an energy of over 30 million electron-volts. The coils of the giant electromagnet can be seen through the opening in the centre. The cyclotron is almost completely surrounded by water tanks to protect the experimenters from the dangerous radiation. (See p. 80.)

soon as the charged sphere begins to spark into the surrounding walls of the protective steel sphere built around it.*

With this highly charged sphere, one can produce a beam of fast-moving particles of any kind—protons, α-particles, lithium nuclei, etc.—by accelerating the corresponding ions in an evacuated glass tube, one end of which enters the charged sphere from below and the other end of which is grounded. As these ions arrive at the bottom of the glass tube, with tremendous kinetic energies, they pass through a thin mica window and enter the underground laboratory, where they can be directed at the substance under investigation. Here, under the opening in the ceiling that lets in the beam of high-energy protons, are crowded a large number of complicated and odd-looking apparatus so designed as to register the results of nuclear disintegration.

THE CYCLOTRON

Whereas the principle of the electrostatic generator can be traced back almost to the beginning of our acquaintance with electricity, the cyclotron, first constructed in California by Dr. Ernest O. Lawrence, is based on an entirely new and original idea. Instead of accelerating the particles by letting them go through a potential gradient of several million volts, Lawrence decided to let the particles run around in a circle and to give them a slight push, by applying some electric tension, each time they passed a definite

* This outside steel sphere is necessary not only as protection against the rain or snow, but also to keep the air dry, thus making unwanted electric discharges more difficult. In the generator shown in Plate IV, the air inside the protective sphere is put under a pressure of several atmospheres, which also helps in the achievement of higher potentials by reducing the sparking distance.

"sign post," thus stepping up their energy at each revolution.

To make a charged particle travel in a circular orbit it is necessary to place it in a uniform magnetic field, for it is known from elementary physics that a magnetic field directed perpendicularly to the direction of motion of a charged particle curves its trajectory and forces it to move in circles. As the particles gain energy from the successive "electric shocks" administered at each new revolution, the deflection produced by the magnetic field becomes smaller and smaller and consequently the radii of the circular orbits grow larger and larger. Fortunately for Lawrence, the increasing length of orbit is exactly compensated by the increasing velocity of motion, so that the particles return to the same sign post of this "electric race track" in equal intervals of time. This makes it possible to use for electric shocks the potential produced by an ordinary high-frequency generator (Figure 22).

In the cyclotron constructed by Lawrence at the University of California and shown in Plate VI, the particle (a proton) makes many successive revolutions before it gets out of the apparatus. After each revolution, lasting only a negligible part of a second, it receives an electric shock, so that toward the end of its journey through the system it accumulates a total potential of several million volts. These high-energy particles come out of the apparatus through a thin mica window, placed at the end of their spiral trajectory, and can be used now for any kind of nuclear bombardment.

The experiments with artificial beams of particles, whereby the type of projectiles needed and their velocities could be conveniently selected at will, resulted in great

progress in our knowledge of various nuclear reactions. In addition to those few mentioned above, dozens and dozens of other interesting nuclear transformations have been extensively studied by these means.

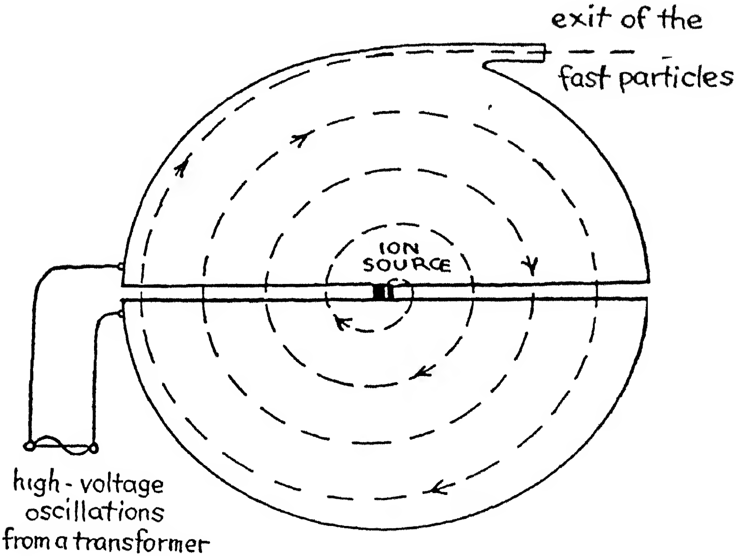


FIGURE 22
The principle of the cyclotron. Particles move in spirals of constantly increasing speed.

NEW "PENETRATING" PROJECTILES

The progress of nuclear physics during the last decade has also been considerably advanced by the discovery of an entirely new kind of nuclear projectile, which, while in many respects similar to ordinary protons, does not, however, carry any electric charge. These *chargeless protons,* or *neutrons,* to use the more conventional term, represent the ideal projectiles for nuclear bombardment, because,

having no electric charge, they will not suffer any repulsion from heavily charged nuclei, and will penetrate without much difficulty into the very interior of the nuclear structure.

Although a hypothesis concerning the possibility of such kinds of particles was expressed by Rutherford as early as 1925, the actual proof of their existence was given only in 1932, when Rutherford's collaborator, Dr. James Chadwick, succeeded in showing that the peculiar radiation emitted by beryllium under α-particle bombardment consists of neutral particles with a mass comparable to that of a proton. The resulting nucleus corresponds to that of ordinary carbon.

At the present time neutrons are usually produced by bringing about the collisions of two deuterons, that is, the nuclei of heavy hydrogen atoms.* Accelerating the ions of heavy hydrogen in one of the modern high-tension generators, one lets them fall on some substance, such as heavy water, that contains in its molecules the bound atoms of heavy hydrogen. In the resulting collisions a very large number of fast-moving neutrons are produced, according to the equation:

$$ {}_1D^2 + {}_1D^2 \longrightarrow {}_2He^3 + {}_0n^1 $$

As we see, another product of this reaction represents the light isotope of helium of mass 3, which is known to be mixed in very small quantities with the ordinary helium of mass 4.

It should be noted here that, owing to the absence of electric charge, neutrons do not produce any ionization of the air along their track and consequently do not leave

* Heavy hydrogen is usually called *deuterium*, and its symbol in nuclear notation is: ${}_1D^2$ (charge 1; mass 2).

any visible trace on passing through a cloud-chamber. They are ordinarily observed only through the traces left by the products of their collisions with the particles of the air that happen to be directly in their way.

THE RESULTS OF NEUTRON BOMBARDMENT

As indicated above, neutrons can easily penetrate any, even the most heavily charged, nucleus and produce devastating effects in its interior. These effects have been investigated mostly by the Italian physicist Enrico Fermi and his collaborators. In the case of lighter elements, the penetration of a neutron is often followed by the ejection either of an α-particle or of a proton as, for example, in the reactions:

$$_{7}N^{14} + {}_{0}n^{1} \longrightarrow {}_{5}B^{11} + {}_{2}He^{4}$$

which represents the transformation of nitrogen into boron and helium; or

$$_{26}Fe^{56} + {}_{0}n^{1} \longrightarrow {}_{25}Mn^{56} + {}_{1}H^{1}$$

which represents the transformation of iron into manganese and hydrogen.

In the heavier elements, the potential walls surrounding the atomic nucleus are too high, and, though they cannot prevent the neutron from entering, they make it impossible for any charged nuclear constituent particle to be thrown out. In this case neutrons entering the nucleus must get rid of their energy through electromagnetic radiation, and the nucleus emits hard γ-rays, as, for example, in the reaction:

$$_{79}Au^{197} + {}_{0}n^{1} \longrightarrow {}_{79}Au^{198} + \gamma\text{-rays}$$

in which a heavier isotope of gold is built. This process of

building the heavier isotope of the bombarded element may often be followed by an adjustment of the electric charge through the emission of an electron (see p. 66 above).

BURSTING A NUCLEUS

In all the nuclear reactions we have thus far discussed, the transformations consisted mainly of the ejection of some comparatively small nuclear structural parts (such as α-particles, protons, or neutrons); up to this point in the development of subatomic physics there had not yet been observed the bursting of the nucleus of a heavy element into two or more approximately equal parts. But quite recently (the winter of 1939) just such "smashing results" were observed by the two German physicists O. Hahn and Lise Meitner, who found that the atoms of uranium, which are already unstable in themselves, would split into two large fragments under the intense bombardment of a beam of neutrons. One of the splinters represents a nucleus of barium and the other presumably that of krypton. *The process is accompanied by an energy liberation exceeding by a factor of hundreds the energy produced in any other known nuclear reaction.* As we shall see in the next chapter, this entirely new type of nuclear transformation gives us, for the first time, some hope for the practical utilization of subatomic energy.

CHAPTER IV

Can Subatomic Energy Be Harnessed?

ENERGY VERSUS GOLD

WE HAVE seen in the last chapter that the progress of physics in the last few decades has revived the golden dream of the medieval alchemists, and has put on a solid scientific basis the fascinating possibility of artificially transforming the elements into one another. But, whereas the alchemists were exclusively interested in the transmutation of base metals into precious gold, it is energy and not gold we are now after. Indeed, the immense stores of energy that might be liberated in nuclear reactions would make gold, or any other material product obtainable from such transformations, relatively worthless.

For example, in the splitting of a lithium atom by the impact of a proton (see Figure 20) there is set free 2.8×10^{-5} erg of energy. Thus, one gramme of lithium, if entirely transformed into helium by proton bombardment, would liberate a grand total of 2.5×10^{18} ergs, which is worth \$7500 according to present energy prices. If any gold or silver were formed along with this liberation of energy, it would represent such a small fraction of the "total profit"—one gramme of gold costs about one dollar—that nobody would be interested in it. On the other hand, the practicable utilization of the subatomic energy hidden in the depths of nuclei would produce a complete revolution in all modern technology and life!

THE LOW RATE OF SUBATOMIC ENERGY LIBERATION

It is a little too early, however, to speculate on the possible technical and economic consequences that would flow from the tapping of subatomic energy sources. There is, of course, no doubt that the energy is there, but, as we have seen in previous chapters, its liberation in the processes of both spontaneous and artificial transformation goes on at such an extremely slow rate that very sensitive physical apparatus are necessary in order even to detect it. In this respect the "nuclear reservoirs" of subatomic energy may be compared to a vast elevated lake from which the water is leaking through a small channel at the rate of one drop per week. There is no sense in installing a large water turbine here until the way is found for opening the channel much wider and letting the available water flow out in a powerful stream.

In order to see whether such channel widening is at all possible in the case of subatomic energy sources, we have to discuss in more detail the various factors governing the rate of nuclear transformation.

THE PROBABILITY OF A CHARGED PROJECTILE'S HITTING A NUCLEUS

Suppose we send a nuclear projectile, such as a proton or an α-particle accelerated to very high energies, through some material, the nuclei of which we intend to bombard. What is the chance that our projectile will score a head-on collision with the nucleus of one of the atoms in our piece of material? We know that the diameter of an atomic nucleus is about 10,000 times smaller than the diameter of the atom itself, so that the target-area of the nucleus is 100

million times (the square of the diameter ratio) smaller than the target-area of the whole atom. As we have no possible method of aiming our projectiles, it follows that the incident particle must pierce on an average 100 million atoms before it will hit a nucleus. But as it passes through the bodies of so many atoms, our projectile will steadily slow down, losing its energy through electric interaction with orbital electrons,* and will, in most cases, come to a stop before it has had a chance to hit a nucleus.

As a matter of fact, the α-particles used in the classical disintegration experiments and the protons produced in modern high-tension generators are stopped after they have passed through only 100,000 atomic bodies. The chance, therefore, of any given projectile's hitting a nucleus before it has lost all its energy is only one in a thousand $\left(\frac{100{,}000}{100{,}000{,}000}\right)$; consequently, of a thousand such projectiles that enter the substance only one will probably score a hit. The bombardment of nuclei, wrapped as they are in their thick envelopes of atomic electrons, is rather like trying to crack walnuts hidden in sandbags by shooting at a pile of such bags with a machine gun.

It is clear then that, although the projectile which scores a direct hit at the nucleus may crack it and liberate an amount of subatomic energy several times surpassing the energy of the impact, *the total liberated nuclear energy will not be nearly enough to compensate for the useless expenditure of the thousand projectiles which missed their aim.* It is true, of course, that by increasing the original energy of the particles used for the bombardment, we can

* This interaction, leading to the ionization of atoms along the track, is responsible, as indicated above (p. 69), for the formation of the visible track in the cloud-chamber.

increase the number of atoms pierced by each of them. But even at the tremendous energies of billions of volts that are observed for some particles of cosmic rays, the total energy balance of transformation will still be extremely unfavourable.

It should also be added here that any attempt to "strip the nuclei of their electronic shells" and to bombard a collection of "bare nuclei" should be labelled as quite visionary. In fact, nuclei deprived of the electronic shells that neutralize their charges would repel each other with such strong force that, in order to keep together one cubic centimetre of such a de-electronized substance, the pressure of many billions of atmospheres would be necessary. This pressure is approximately equivalent to the weight that the moon would have if it were placed on the surface of the earth, and is clearly unattainable by any means at our disposal.

PENETRATING THE NUCLEAR FORTRESS

Let us consider now the case of the "lucky" projectile that happens to meet a nucleus before it has lost all its energy through the "intra-atomic friction" described above. Will it always be able to penetrate the nucleus and produce the necessary transformation? The answer is again no, for atomic nuclei are very strongly fortified against any intrusion of other charged particles from outside. The repulsive forces between the electric charge of the nucleus and that of the projectile become stronger and stronger as the projectile approaches the nuclear boundaries, and are apt to throw the incident particle back, producing an ordinary scattering phenomenon. Thus, *only a very small proportion of those particles which do score a direct hit manage to pass*

through this barrier of the repulsive electric forces and enter the nuclear interior.

A detailed understanding of this process by which bombarding particles penetrate the barriers surrounding atomic nuclei presented some very serious difficulties from the point of view of classical mechanics—just as did the "leaking out" of α-particles described in a previous chapter (p. 64)—and their solution became possible only through the application of the modern quantum theory. The quantum-mechanical calculations carried out in 1928 by the author led to a rather simple formula permitting us to estimate *the proportion of projectiles that would penetrate the nuclear interior, expressed in terms of the charge of the bombarded nucleus and of the charge, mass, and energy of the projectiles used.*

This formula demonstrates in particular that the probability of penetration decreases very rapidly with the increasing atomic number (nuclear charge) of the bombarded element. This explains why, under the bombardment of α-particles and protons, only the lightest elements could be disintegrated. On the other hand, the efficiency of bombardment increases very rapidly with the increasing energy of the projectiles; and at sufficiently high energies (25 million volts for lithium, 50 million volts for iron, and 100 million volts for lead) almost any direct hit will mean disintegration.

RESONANCE DISINTEGRATION

It must be mentioned here that such hundred-percent penetrations can sometimes also occur at considerably lower energies of the bombarding particles. This happens in cases where the barrier surrounding the nuclear fortress

possesses certain *"weak spots,"* which are usually known as *resonance channels.* It was shown by Gurney that, in the processes of nuclear bombardment, the penetration of the barrier by the incident particles can be considerably facilitated if their energy is exactly the same as the energy corresponding to one of the harmonic vibrations within the bombarded nucleus itself. These harmonic vibrations of the struck nucleus are of the same kind as those of a bell or tuning-fork struck by a hammer, and this phenomenon is known as *nuclear resonance* because of its similarity to the resonance phenomena in ordinary mechanics, in which the amplitude of vibration rapidly increases if the vibrating body is subjected to a sequence of shocks following each other within a certain definite period.

The study of various nuclear reactions revealed that many nuclei actually possess such "resonance channels" and can be disintegrated much more easily if the bombardment is carried out with projectiles of just the proper energy. In many cases the use of "resonance bombardment" can increase the probability of disintegration by a factor of many hundreds or even thousands; but it must not be forgotten that all these increases of disintegration efficiency that result from using either extremely high energies or especially selected "resonance values" pertain only to the probability of penetration *after* the head-on collision has taken place. There always remains the unfavourable ratio of one to a thousand as far as the probability of such a collision is concerned, which makes the total efficiency extremely small in any case.

All these considerations, taken together, mean that *nuclear transformations produced by bombardment with fast-moving charged particles must necessarily have a very*

small efficiency; that is to say, although they are extremely interesting from a purely scientific point of view, they can hardly be considered to have any practical importance.

BOMBARDMENT BY NEUTRONS

In contrast to the charged nuclear projectiles, *neutrons represent the ideal particles for nuclear bombardment.* First, owing to their complete lack of electric charge, they will pierce the electronic shells of atoms without any loss of energy (as will be remembered, neutrons do not leave any visible track in a cloud-chamber); secondly, when they do finally collide with a nucleus, they will not be stopped by any repulsive electric forces. It follows that practically every neutron shot into a thick layer of matter will sooner or later find a nucleus in its path, and penetrate it.

But precisely because of this penetrativity of neutrons, and the ease with which they are therefore captured,* free neutrons are very rare in nature, and there is no such element as "neuterium." It should also be noted that a free neutron cannot even exist as such for more than about half an hour because, being essentially unstable, it very soon emits a free negative charge (an ordinary electron), thus transforming itself into a proton (Figure 23).

In order to produce a beam of neutrons for bombardment purposes we therefore first have to extract them from the interior of ordinary nuclei, where they are usually to be found, and this operation can be performed only by bombarding the latter with protons or α-particles. But in order to shoot *one* neutron out of the nucleus by proton

* As we have seen in the last chapter (p. 83), a neutron, upon entering a nucleus, usually remains there, ejecting in its place either a proton or an α-particle or finally discharging its extra energy through a γ-ray emission.

or α-particle bombardment, many thousands of incident charged particles are necessary, and we are back to our original difficulty.

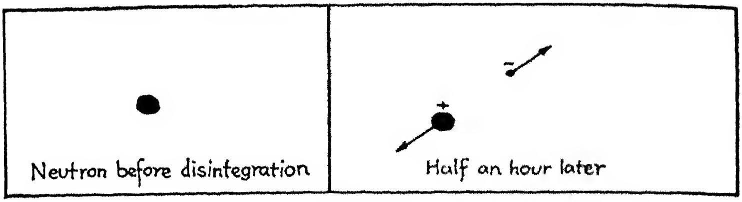


FIGURE 23
Spontaneous splitting of a free neutron into a proton and an electron.

MULTIPLICATIVE NUCLEAR REACTIONS

The preceding discussion will have explained why our only hope of obtaining practical results from neutron bombardment is to discover some nuclear reaction in which *the neutrons are, so to speak, self-multiplied.* If every incident neutron were only able to kick out from the bombarded nucleus two or more "fresh" neutrons, and if these new particles could in their turn produce still more neutrons by colliding with other nuclei, so that the number of acting neutrons rapidly increased in geometric proportion (Figure 24), our problem would be solved. The situation here is rather similar to the multiplication problem of human races; and just as the growth of the population is possible only if the average number of babies born per family is not less than two, so a nuclear multiplicative process requires that not less than two neutrons should be emitted by each nucleus that is "fertilized" by collision with one of the incident neutrons of the previous generation.

As recently as 1939 it was generally believed that such a

multiplicative process did not usually take place in nature, and that nuclear reactions represented a strictly one-to-one relationship (i.e., one particle shot out for every one going in). As was suggested in the last chapter, however, recent experiments by Hahn and Meitner with the neutron bombardment of uranium and thorium have shown that

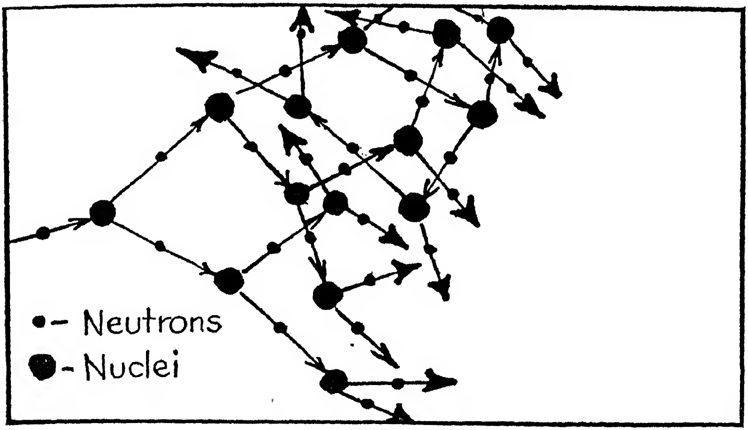


FIGURE 24
Multiplicative disintegration possible for certain cases of bombardment of matter by neutrons.

the nuclei of these elements are considerably more fragile than those of any other. When struck by neutrons, these nuclei are apt to split into two large parts, and this major breakdown is also accompanied by the ejection of smaller nuclear splinters in the form of two, three, and sometimes even four other neutrons. Thus, we have here precisely the case in which the multiplicative process we have been seeking actually does take place; and the proper treatment of these nuclear reactions may lead us to the possibility of the large-scale liberation of subatomic energy.

Two questions, however, immediately arise, and the first concerns the reasons why a piece of uranium, when bombarded by neutrons in our laboratories, does not immediately explode, thereby wiping out the lives of the experimenters as well as of any other living being within many hundreds of miles. For, theoretically, such a multiplicative reaction, once started, should take the form of a terrific explosion, all the tremendous amounts of energy stored in uranium atoms (10^{18} ergs per gramme, which is equivalent to the explosion energy of a ton of dynamite!) being liberated in a small fraction of a second.

The answer to this important question is, first, that the ordinary uranium we have in our laboratories is *wet*—not wet, of course, in the ordinary sense of this word, but rather in the sense that its active part is mixed in with a large amount of inactive material (as a piece of wood may be saturated with water), which absorbs most of the newly created neutrons and takes them out of active service. It is known that ordinary uranium is composed of a mixture of two isotopes UI and UII (see Figure 16) with atomic weights, respectively, of 238 and 235. The lighter isotope UII is present in the mixture in a small concentration of only 0.7 percent; and it is certain that this is the isotope responsible for the observed splitting and intense neutron emission. The heavier isotope UI, making up 99.3 percent of the mixture, also catches the incident neutrons, but, instead of splitting into parts with high energy liberation, it retains the neutrons and emits the surplus of energy in the form of hard γ-radiation. Thus, only very few of the produced neutrons can take part in the actual multiplicative process; and, in order to obtain a progressive multiplicative process, we must separate the lighter active iso-

tope from the heavier one, a task which, with the present means at the disposal of experimental physics, is, if not impossible, at any rate rather difficult. The modern technique of isotope separation involves a large number of successive diffusions, during which the concentration of the lighter isotope, in the diffused fractions of material, gradually increases.*

Work on the separation of uranium isotopes is now under way in many laboratories and will probably soon lead to extremely interesting results.† There is little ground for fear, however, that one fine day the laboratory which first produces a highly concentrated UII isotope will jump into the air together with the whole city in which it is situated. For the steadily increasing concentration of the lighter uranium isotope will most probably be accompanied by a correspondingly slow increase of the liberation of subatomic energy; and, before the developed heat becomes too intense for safety, the separation process will be stopped in time to avert any danger of explosion.‡ Let us at least hope it will happen this way!

The second important point regarding the possibility of a self-sustaining neutron-multiplication process in uranium concerns the amount of uranium needed. With

* The rate of diffusion through porous walls depends essentially on differential atomic weight, the lighter isotope going through more rapidly. However, owing to the small relative difference of the atomic weights of the two uranium isotopes (less than one percent), the separation in this case is bound to be extremely slow.

† On March 15, 1940, such a separation was finally announced by Drs. O. Nier, E. T. Booth, J. R. Dunning, and A. V. Grosse, but for extremely small quantities (0.000,000,001 gramme).

‡ This will happen spontaneously, because the temperature developed in the reaction will melt all the vessels in which the separation of isotopes is taking place. It should be noted that the nuclear explosion process would not need a special neutron source to start it off. In fact there are so many neutrons passing occasionally by (for example, in the cosmic rays) that the "spark" can be struck almost any moment.

a small piece of uranium, most of the neutrons produced in its interior will escape through the surface before they have had a chance to hit a nucleus. The progress of the multiplication process will then be stopped for the same reason that a small tribe cannot grow if it continually loses its younger members in the surrounding forest. Since there are no walls to prevent the neutrons from escaping into surrounding space, it becomes necessary to use such large pieces of uranium that a neutron produced in its interior will be sure to meet a nucleus before it can have come to the surface. But this would require *several hundred tons of pure uranium* 235, which is not a very easy thing to acquire, especially in the form of separate isotopes.

THE PRICE OF URANIUM ENERGY

Supposing that these two difficulties—large-scale isotope separation and the retention of active neutrons—standing in the way of the practical utilization of the subatomic energy of uranium (and of its sister element thorium) were to be overcome by technical genius, and a method were found for running our engines on "uranium fuel," how much would it cost?

Uranium is not a very cheap material; according to present market prices, a pound of uranium oxide, containing 95 percent pure uranium, costs about two dollars, which is equivalent to the price of one ton of coal at the mine. As only 0.7 percent of uranium is active in neutron multiplication, the total subatomic energy released in the process by the pound of uranium oxide will amount to 3×10^{18} ergs. On the other hand, a ton of coal (900,000 grammes), costing the same as a pound of uranium oxide, will liberate only 3×10^{17} ergs, so that *the subatomic*

energy that might be obtained from uranium would be about 10 times cheaper than the energy of coal.

It should be added, however, that if uranium were completely to replace coal as a source of energy, at the present rate of consumption, the reserves of uranium ore on our planet would be entirely exhausted in less than a century.

RECAPITULATION: THE STRUCTURE OF THE ATOM

Let us now plunge once more and for the last time into the depths of matter, briefly reviewing the main conclusions we have reached in the last three chapters. First we found that matter, seemingly so homogeneous in the light of everyday experience, consists in point of fact of very, very small granules known to scientists as molecules. No microscope is strong enough to make visible these constituent particles of matter, and very elaborate and subtle methods of modern physics are necessary to prove their existence and to study their characteristic properties.

There are, for example, about 600,000,000,000,000,000,000,000 (23 zeros!) molecules of H_2O in each cubic inch of water, and they are all animated by a vigorous and disorderly thermal motion that should make them resemble a mess of freshly caught fish in an angler's basket. This molecular motion gradually slows down as matter gets colder, but we would need temperatures as low as 459°F. below zero to bring these restless particles to a complete standstill. On the other hand, raising the temperature makes the molecules move more and more briskly and leads at last to their mutual separation. We say then that the molecules form a gas, or vapour, in which each particle moves more or less freely through space and collides frequently with every other particle that comes its way.

There are as many different types of molecules as there are different chemical substances (i.e., hundreds of thousands of them); but if we look more closely into any given molecule we find that it is always composed of a limited number of somewhat smaller constituent particles called atoms. There are only ninety-two kinds of atoms, corresponding to the ninety-two pure chemical elements, and through the different combinations of these atoms arise the innumerable complex compounds familiar to our chemists. The various redistributions of the atoms in the complex molecules is observed by us as specific chemical reactions, or the transformations of one chemically complex substance into another. But, despite all the attempts of medieval alchemy, atoms themselves had stubbornly refused to be transformed into one another, and this led chemists to the erroneous conclusion that atoms were really elementary and indivisible particles, as was suggested by the Greek meaning of their name.

The progress of physics, however, shook this point of view, which prevailed in science throughout the last century, and we know now that an atom is actually a rather complicated mechanical system consisting of a central nucleus with a swarm of electrons revolving around it under the action of electric forces. Now it was these atomic nuclei that represented the citadel of indivisibility, but even this last stronghold of the Democritean idea gave up under the attack of that restless investigator of matter, Lord Rutherford of Nelson.

In the year 1919 the first nitrogen nucleus was broken up by him under a bombardment of tiny projectiles, known as α-particles; and the following two decades saw an immense development of what is known as nuclear

physics. Many dozens of nuclear reactions have been produced and investigated in great detail, with the result that we now know more about the atomic nucleus than had been known about atoms themselves a few decades ago.

The two most important facts that distinguish nuclear reactions from ordinary chemical reactions between molecules are the tremendous amounts of subatomic energy liberated in the former transformations, and the tremendous difficulties encountered in the attempts to produce these reactions on a large scale. In fact, owing to the thick layer of electronic shells surrounding individual nuclei, only a very small proportion of the projectiles used for bombardment purposes can score direct hits on the atomic nucleus, and of thousands of projectiles that attain their goal probably not more than one will actually produce the desired transformation. It is true that during recent years the discovery of neutrons and of the multiplicative reactions connected with this new type of particle gave us some hope for the possible technical utilization of the huge stores of subatomic energy hidden in the interiors of atoms, but these have so far remained only hopes.

For though the study of the peculiar splitting properties of uranium and thorium nuclei brought us very close to the possible solution of the problem, these two elements were found to be exceptional in showing this instability and they are, moreover, rare in the world. The basic problem of how to liberate the nuclear energy of all the other, more common elements is still left open.

We shall, however, see in the following chapters, in which the impatient reader may at last return to the Sun, that the large-scale transformation of common elements, which so stubbornly retain their hidden energy even under

sating variables indicates that we are dealing here with certain peculiar conditions that could be attained only once during the whole evolutionary life of a star.

The exact character of the conditions that could lead to the instability of these giant stellar bodies is not quite clear as yet, but the hypothesis recently advanced by the author strongly suggests that *the pulsations come as the result of a conflict between the nuclear and the gravitational energy-producing forces in the stellar interior.* It can, as a matter of fact, be shown that the region of the Russell diagram occupied by pulsating stars is characterized by the circumstance that the amount of energy liberated by thermonuclear reactions and the amount liberated by the gravitational contraction of the stellar body are of about the same order of magnitude. We might say that in these cases the stars "do not know which kind of energy production it is better to choose," and are "oscillating between the two possibilities." But this attractive hypothesis needs additional confirmation, and cannot be considered as definitive before some rather long and tedious calculations have been performed.

CHAPTER V

The Alchemy of the Sun

SUBATOMIC ENERGY AND SOLAR HEAT

THE discovery of the enormous stores of energy that can be set free in the processes of nuclear transformation gives us a key to the possible solution of the ancient riddle concerning the sources of solar radiation. We have, indeed, already mentioned that the nuclear reactions leading to the transformation of one element into another are usually accompanied by a liberation of energy that surpasses by a factor of many millions the energy set free in ordinary chemical reactions between molecules. Thus, whereas a Sun made of coal would have burned up completely in fifty or sixty centuries, a Sun that takes its energy from subatomic sources can keep going strong for billions of years.

But we also know that the ordinary radioactive elements, such as uranium or thorium, are not abundant enough to account for the tremendous energy production in the Sun*; and we are left with the only possible conclusion that the observed liberation of energy must be due to the induced transformations of the ordinarily stable common elements. We must therefore imagine the interior of the Sun as some gigantic kind of natural alchemical laboratory where the transformation of various elements

* These elements are, however, sufficiently abundant to be mainly responsible, through the heat they develop, for the fact that the interior of our globe is still in a state of hot molten lava.

into one another takes place almost as easily as do the ordinary chemical reactions in our terrestrial laboratories.

What, then, are the extraordinary facilities of this cosmic energy plant, which produces the phenomena of nuclear transformation on such a large scale and sets free so vast an amount of subatomic energy? If we remember what was said in the first chapter about the physical conditions obtaining in the interior of the Sun, we shall see at once that the most striking characteristic of these regions is their extremely high temperatures, which cannot even be approached under our terrestrial conditions. May it not be these high temperatures that are responsible for the high rates of nuclear transformation going on in the solar interior? We know that all ordinary chemical reactions between molecules are greatly accelerated by heating; and if a log of wood or a piece of coal will begin to burn when it is heated to several hundred degrees in an ordinary furnace, why cannot we expect that the matter heated to many millions of degrees in the solar interior will start to "burn" in the nuclear sense?

THERMONUCLEAR REACTIONS

The answer to this important question was first proposed by two young scientists, Robert Atkinson and Fritz Houtermans, in 1929. Their explanation was to the effect that, at the very high temperatures obtaining in the interior of the Sun, the kinetic energy of thermal motion becomes so great that the violent mutual collisions among the irregularly moving particles of matter are as destructive of nuclei as are the impacts of atomic projectiles in ordinary bombardment experiments. In fact, at a temperature of 20 million degrees the average kinetic energy of thermal

motion amounts to 5×10^{-9} erg, which is not very far from the value of 10^{-8} erg actually observed in our laboratories to accompany the artificial transformation of elements. But, whereas the ordinary bombardment method might be compared to a bayonet attack of a single line of soldiers upon a comparatively large group of people, the thermonuclear process is more nearly analogous to a violent hand-to-hand fight going on simultaneously throughout all parts of a highly excited and quarrelsome crowd.

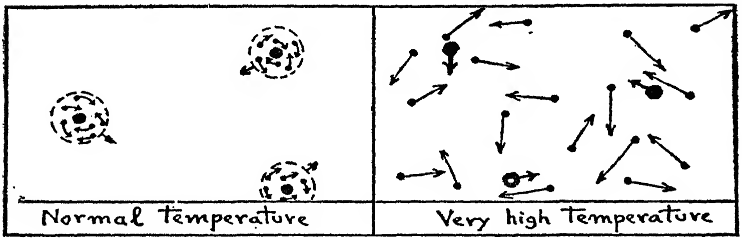


FIGURE 25
Thermal ionization of a gas.

It should be remarked, too, that, at these very high temperatures at which the thermonuclear reactions take place, matter no longer consists of atoms and molecules in the proper sense of these words. At much lower temperatures the electronic shells of individual atoms will already have been completely stripped off by the mutual thermal collisions; and matter will then consist of a mixture of irregularly moving *bare nuclei* (completely ionized atoms), with unattached electrons rushing in all directions among them (Figure 25). The "naked" nuclei, unprotected by electronic shells, will no longer be cushioned against thermal collisions, and the violent direct impacts will often lead to fatal results.

The persistency of the thermal collisions makes the thermonuclear reactions infinitely more effective than the ordinary bombardment process, where the initial energy of the artificially accelerated projectiles is completely lost after their passage through the electronic flesh of only a hundred thousand atoms of the bombarded substance. If, for example, we heat a mixture of hydrogen and lithium to a sufficiently high temperature, the violent thermal collisions among the particles of these two elements will go on and on without stopping until all the available nuclei have been transformed into helium. The subatomic energy liberated in the process will keep our reacting substances sufficiently hot to insure its continuance, so that all we need here is to raise the temperature of our mixture sufficiently high to get the reaction started.

THE TEMPERATURES NECESSARY FOR THERMONUCLEAR REACTIONS

In order to consider the question of the importance for the life of our Sun of the thermonuclear reactions among the various elements—and also if we wish to discuss the possibility of the practical utilization here on earth of these same processes—we must know first of all the temperatures at which these transformations would take place at a reasonably high rate.

As in the case of ordinary nuclear bombardment previously discussed, the rate of the thermonuclear reactions will be essentially determined by the penetrability of the barriers surrounding the colliding nuclei. It has already been indicated that the theory of nuclear transformations developed by the author permits us to calculate the probability of such penetrations in terms of the kinetic energy

and the electric charges of the colliding particles. We have also seen that this probability increases extremely rapidly with the increasing energy of the colliding particles (i.e., with the temperature of the mixture), but falls quickly with their increasing electric charges. Thus, we should expect, on heating a mixture containing different types of nuclei, to observe first the reactions between the lightest nuclei, which carry the smallest charges; the reaction between hydrogen and lithium mentioned above will therefore be one of the first to take place. As the temperature of the mixture rises still further, we should expect more effective penetration of the heavier nuclei by thermal protons and also the beginning of activity between α-particles and the lightest elements. Finally, at still much higher temperatures, collisions between the heavy nuclei themselves might become of importance.

In order to calculate from this penetration formula the rate of thermonuclear reaction between any two given types of nuclei, it is not sufficient, however, to know only the average kinetic energy of the particles at a given temperature. As we have seen in Chapter II, the particles of a hot gas do not all move with exactly the same velocity, but show a rather broad velocity dispersion known as the Maxwell distribution. It is true, of course, that the number of particles possessing anomalously large energies is comparatively small; but we must not forget that the effectiveness of collision rapidly increases with the increasing energy of impact. Thus, although few, these high-energy particles can be of great importance for the total disintegration balance. In Figure 26 the curve *A* represents the familiar Maxwellian energy-distribution of thermal motion (compare Figure 6), giving the relative number of the particles

of gas possessing different values of energy (E). The curve *B*, on the other hand, gives us the disintegration ability (penetrativity of nuclear barriers) of particles corresponding to these energies. Finally, $A \times B$, the product of these two curves, represents the total disintegration effect (num-

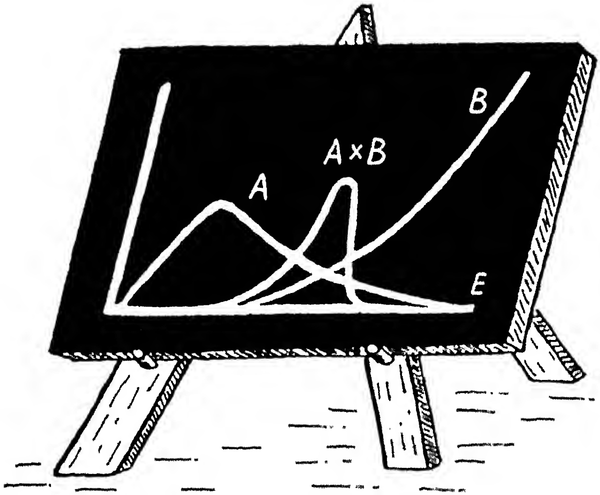


FIGURE 26
The maximum number of disintegrations ($A \times B$) takes place for thermal energy for which the particles' penetrativity of nuclear barriers (B) is already sufficiently high, whereas their number (A) is not yet too small.

ber of particles times their relative effectiveness). We see at once that the maximum effect corresponds to a certain intermediate energy value for which the number of particles is not yet too small and their penetrativity of barriers is already sufficiently high.

Thus combining Maxwell's distribution law with the author's formula for penetrativity, Atkinson and Houter-

mans succeeded in obtaining *an expression for the dependence of the disintegration rate on the temperature of the mixture and on the atomic numbers of the participating elements.** We shall not terrify the reader by writing down their formula in all its mathematical magnificence, but shall rather give here the numerical results of its application to one characteristic nuclear reaction.†

We shall select for this purpose the reaction between hydrogen and lithium, which has already been mentioned a few times and is, besides, one of the most effective reactions, owing both to its high reaction rate and to the high values of energy liberated per nucleus. One gramme of a mixture consisting of seven parts of lithium and one part of hydrogen will, if completely transformed into helium, produce 2.2×10^{18} ergs of subatomic energy. But even at a temperature of several thousand degrees (the highest available in our laboratories), the thermonuclear reaction will go so slowly that it would require billions of billions of years to produce the complete transformation. At so slow a rate, the energy liberation of one ton of the mixture would amount to only a few ergs per century, not enough even to raise a dead fly from the floor to the table. At one million degrees, however, the energy flow from several pounds of the hydrogen-lithium mixture would be sufficient to run an automobile engine. And, finally, at the central solar temperature of 20 million degrees, hydrogen and lithium will be transformed into helium in a few sec-

* The rate of energy production depends also on the density of the matter, being proportional to the product of densities of the reacting substances.

† The numerical results given here are actually calculated not on the basis of the original formula as given by Atkinson and Houtermans, but on the basis of a new revised expression, corrected according to the latest development of nuclear physics.

onds, and the energy liberation must take the form of a terrific explosion.

If, however, we apply the same formula to the collisions of protons with the nuclei of heavier elements, we find that even at central solar temperatures the reaction between hydrogen and chlorine, for example, will take 10^{25} years to transform 50 percent of the mixture, and the penetration of protons into the heavy nuclei of lead will require an unbelievably long time—no less than 10^{250} (!) years. We find also that at this temperature the penetration of thermal α-particles is negligibly small even for collisions with the lightest nuclei, and that it becomes important only for a temperature above 50 million degrees.

HOW TO MAKE A "SUBATOMIC MOTOR"

"Excellent!" the reader may already have exclaimed. "Then all we have to do is to load the furnace of a steam engine with a lithium-hydrogen mixture and heat it up to several million degrees. Is that so difficult?" (Figure 27.)

Well, it is not difficult, of course, to acquire an old steam engine for such an experiment; neither is it very hard to obtain the necessary nuclear fuel, since the solid lithium-hydrogen compound LiOH can be bought in almost any drug store. But what about the temperature of several million degrees? No chemical process, such as the combustion of coal, is capable of developing such high temperatures; and if we try to heat our furnace by the electric method, the wires—even those made of the most refractory materials—will have melted (and even evaporated) before we have attained several thousand degrees of temperature. The same fate will also befall the walls of the furnace itself, and there will be no means of keeping the

reacting gases within a given volume. The melting of the walls will permit the immediate expansion of the hot gases, and the temperature will inevitably fall.

As all these undesirable events will have taken place long before the temperature has been given a chance to

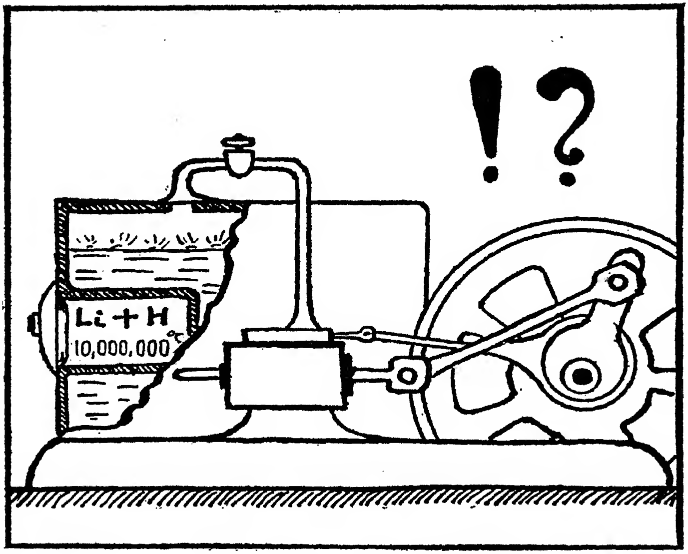


FIGURE 27
A dream of a subatomic motor. No walls will, however, withstand such heat.

rise to the necessary high values, it is very difficult to see how thermonuclear reactions can be forced to go on under laboratory conditions. This miracle, at least, would seem to be beyond the powers of modern technique.

THE SOLAR FURNACE

The insurmountable difficulties in our way when we attempt to construct a thermonuclear furnace at home do

not, however, exist in the case of the Sun, which is just such a giant furnace. This cosmic furnace actually possesses "gaseous walls"—the outer layers of its body—which are kept together by the forces of mutual gravitational attraction (Figure 28).

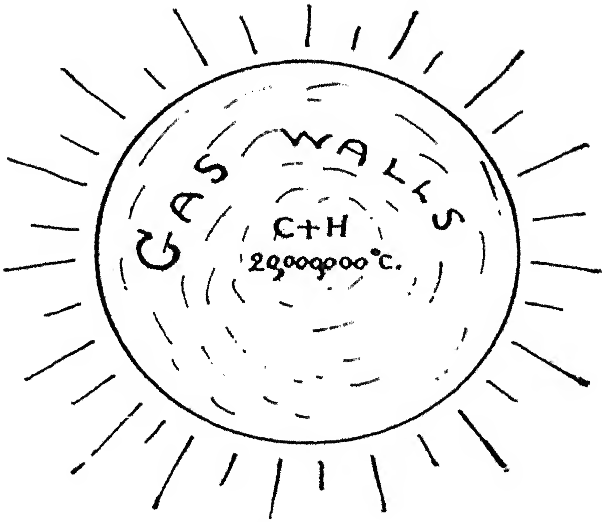


FIGURE 28
The subatomic generator of the Sun. The gas walls are held together by gravity.

The forces of gravity also provided the mechanism that was necessary to bring about the original rise of temperature to the value at which the thermonuclear reactions could begin. We have seen in Chapter I that the Sun must have begun life as a comparatively cool giant mass of gas, which gradually became hotter and hotter because of progressive gravitational contractions. As soon as the central temperature of this contracting Sun became sufficiently

high to keep the nuclear reactions going, the liberation of subatomic energy stopped further contractions and the Sun came into its present stable state.

We should also note that the outside layers of our Sun provide an ideal regulative mechanism for the liberation of energy in its interior. If, for some reason, the rate of thermonuclear processes in the central regions of the Sun were to drop, there would follow an immediate contraction of the whole solar body, and the resulting increase of temperature would rapidly bring the energy production back to its original value. If, on the other hand, the central energy production rose above the "red mark," the Sun would expand and thereby bring down its central temperature.

In this sense our Sun represents the most ingenious, and perhaps the only possible, type of "nuclear machine."

THE SOLAR REACTION

We have now learned that, at the temperatures obtaining in the solar interior, the thermonuclear reactions between protons and the nuclei of various light elements would proceed sufficiently rapidly to achieve the necessary energy production. From the theory of solar constitution as developed by Eddington we have also learned that the body of the Sun contains a considerable amount (about 35 percent) of hydrogen, and it now remains to find the other participants of the reaction. To do this, one must calculate the rates of energy production for the multitude of possible nuclear reactions, and compare them with the actually observed radiation of the Sun.

It is clear, for example, that the hydrogen-lithium reaction is too fast to be the main energy-producing reaction;

for, as we have seen, at 20 million degrees the transformation of lithium and hydrogen into helium would take only a few seconds, so that, if there were any appreciable amount of lithium in the central regions of the Sun, all its subatomic energy would be liberated in the form of a terrific explosion that would tear our Sun into a thousand pieces. We know, therefore, that our Sun cannot contain any appreciable amount of lithium in its interior, just as we know that a slowly burning barrel surely cannot contain any gunpowder.*

On the other hand, the liberation of thermonuclear energy in the reaction between protons and the nuclei of oxygen, for example, is too slow to account for the Sun's radiation.

"But it should not be so difficult after all to find the reaction which would just fit our old Sun," thought Dr. Hans Bethe, returning home by train to Cornell from the Washington Conference on Theoretical Physics of 1938, at which he first learned about the importance of nuclear reactions for the production of solar energy; "I must surely be able to figure it out before dinner!" And taking out a piece of paper, he began to cover it with rows of formulas and numerals, no doubt to the great surprise of his fellow-passengers. One nuclear reaction after another he discarded from the list of possible candidates for the solar life supply; and as the Sun, all unaware of the trouble it was causing, began to sink slowly under the horizon, the problem was still unsolved. But Hans Bethe is not the man to

* Spectroscopic evidence does, however, indicate the presence of a certain amount of lithium in the comparatively much cooler regions of the solar atmosphere. As this element cannot possibly be present in the hot interior regions, we must conclude that its abundance is limited to the outer layers (compare Chapter VII).

miss a good meal simply because of some difficulties with the Sun and, redoubling his efforts, he had the correct answer at the very moment when the passing dining-car steward announced the first call for dinner. Simultaneously with Bethe, the same thermonuclear process for the Sun was proposed in Germany by Dr. Carl von Weizsäcker, who was also the first to recognize the importance of cyclic nuclear reactions for the problems of solar energy production.

The thermonuclear process mainly responsible for the energy production of the Sun, it was discovered, is not limited to a single nuclear transformation, but consists of a whole sequence of linked transformations which together form, as we say, *a reaction chain*. One of the most interesting features of this sequence of reactions is that it is *a closed circular chain,* returning us to our starting-point after every six steps. From Figure 29, representing the scheme of this solar reaction chain, we see that *the main participants of the sequence are the nuclei of carbon and of nitrogen, together with the thermal protons with which they collide.*

Starting, for instance, with ordinary carbon (C^{12}), we see that the result of a collision with a proton is the formation of the lighter isotope of nitrogen (N^{13}), and the liberation of some subatomic energy in the form of a γ-ray. This particular reaction is well known to nuclear physicists, and has also been obtained under laboratory conditions by the use of artificially accelerated high-energy protons. The nucleus of N^{13}, being unstable, adjusts itself by emitting a positive electron, or positive β-particle, and becoming the stable nucleus of the heavier carbon isotope (C^{13}), which is known to be present in small quantities in ordinary coal. Being struck by another thermal proton, this

carbon isotope is transformed into ordinary nitrogen (N^{14}), with additional intense γ-radiation. Now the nucleus of N^{14} (from which we could just as easily have begun our description of the cycle) collides with still another (third)

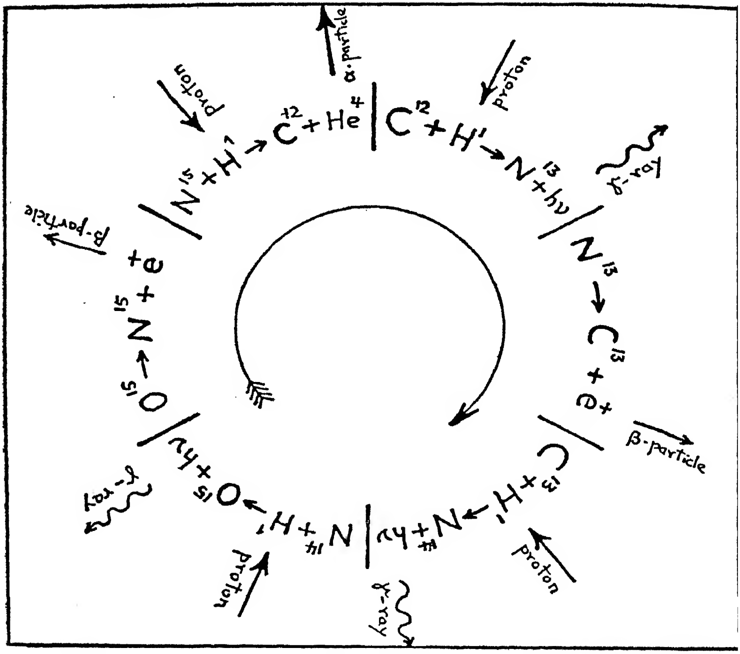


FIGURE 29
The cyclic nuclear reaction chain responsible for the energy generation in the Sun.

thermal proton and gives rise to an unstable oxygen isotope (O^{15}), which very rapidly goes over to the stable N^{15} through the emission of a positive electron. Finally, N^{15}, receiving in its interior a fourth proton, splits into two unequal parts, one of which is the C^{12} nucleus with which

we began and the other of which is a helium nucleus, or α-particle.

Thus we see that *the nuclei of carbon and nitrogen in our circular reaction chain are for ever being regenerated, and act only as catalysts,* as chemists would say. The net result of the reaction chain is the formation of one helium nucleus from the four protons that have successively entered the cycle; and we may therefore describe the whole process as *the transformation of hydrogen into helium as induced by high temperatures and aided by the catalytic action of carbon and nitrogen.*

It should be clear that, with a sufficient amount of hydrogen present, the rate of the cycle will depend essentially on the proportion of carbon (or nitrogen) in the matter of the Sun. Accepting the figure of one percent of carbon as given by astrophysical evidence, Bethe was able to show that the energy liberation of his reaction chain at the temperature of 20 million degrees *exactly coincides with the actual amount of energy radiated by our Sun.* Since all other possible reactions lead to results inconsistent with the astrophysical evidence, it should be definitely accepted that *the carbon-nitrogen cycle represents the process mainly responsible for solar energy generation.* It should also be noted here that, at the interior temperature of the Sun, the complete cycle shown on Figure 29 requires about 5 million years, so that at the end of this period each carbon (or nitrogen) nucleus that originally entered the reaction will emerge from it again as fresh and untouched as it was to start with.

In view of the basic part played in this process by carbon, there is something to be said after all for the primitive view that the Sun's heat came from coal; only

we know now that the "coal," instead of being a real fuel, plays rather the role of the legendary phœnix.

THE EVOLUTION OF THE SUN

What sort of changes may we expect in our Sun as a consequence of the slow consumption of its hydrogen "fuel"? At first sight this would seem to lead inevitably to a progressive decline of energy production, so that our Sun should be slowly dying, growing colder and dimmer every moment. The investigations of the author, however, have shown that this is not so, and that, as a matter of fact, our Sun must be steadily increasing in luminosity.

For the rate of thermonuclear transformations depends not only on the amount of the reacting element (hydrogen in our case), but also on the temperature causing the reaction. If, let us suppose, the decrease of the total amount of "fuel" were somehow to cause an *increase* of the temperature, the last remaining pieces would burn much more brightly and give much more heat than when the "furnace" was loaded to the top. An arrangement of precisely this sort is shown in Figure 30, where the opening of the air-blower of an ordinary coal furnace is so connected with the grate on which the coal rests that a decrease in the weight of coal makes a larger opening in the blowpipe, creates more draught, and causes the fire to burn more strongly.

An analogous mechanism exists in the solar furnace, with the difference that the regulating mechanism is provided by the opacity of the matter forming the body of the Sun. Helium, formed in the solar interior as a result of the hydrogen consumption, is less transparent than was the

original hydrogen,* and the energy liberated in the thermonuclear reaction undergoes more difficulties in its journey toward the surface. The more the hydrogen is transformed

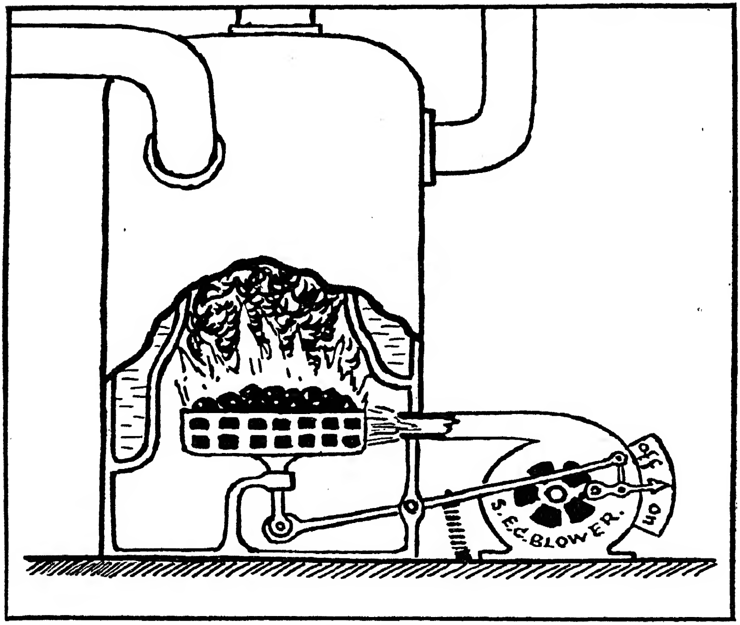


FIGURE 30
A furnace that burns stronger when there is less coal.

into helium, the more opaque becomes the blanket, and the resulting accumulation of energy in the central parts of the Sun leads to a corresponding rise in temperature and an increasing rate of energy production.

* Under terrestrial conditions both helium and hydrogen gases are quite transparent; but, under the conditions of high density and high temperature obtaining in the solar interior, the thick layers of these gases effectively absorb radiation, helium being several times more opaque than hydrogen.

The calculations carried out by the author on the basis of the accepted theory of the internal constitution of our Sun indicate that *the solar radiation must be gradually increasing with time and will have increased a hundredfold by the time the amount of hydrogen is about to fall to zero.* These calculations also indicate that, with its decreasing hydrogen content, the Sun's radius must first increase by several percent and then begin slowly to diminish.

These results are represented graphically in Figure 31, where the luminosity and radius of the future states of our Sun are plotted on a logarithmic scale. We see from this that the new development of the problem of solar energy production leads us to conclusions quite opposite to those maintained by classical theory. Instead of being frozen to death by the decrease of solar activity, life on earth is rather doomed to burn out because of the intense heat which will be developed by our Sun toward the end of its normal evolution. The increase of solar radiation by a factor of a hundred will bring the temperature of the surface of our planet well above the boiling-point of water, and, although at this temperature the solid rocks forming the crust of the earth will probably not yet melt, the oceans and seas will boil.

It is difficult to imagine any living being left on the surface of the earth under such conditions, though the progress of technique during the next few billions of years that separate us from these unpleasant circumstances may make it possible to dig safe, air-conditioned underground cellars for humanity or even to transport the whole population of the earth to some distant planet of our system where the heat will not be so intense. Moreover, we must remember that the changes in solar radiation are going

forward extremely slowly. It can be calculated that the increasing solar activity raises the average surface tempera-

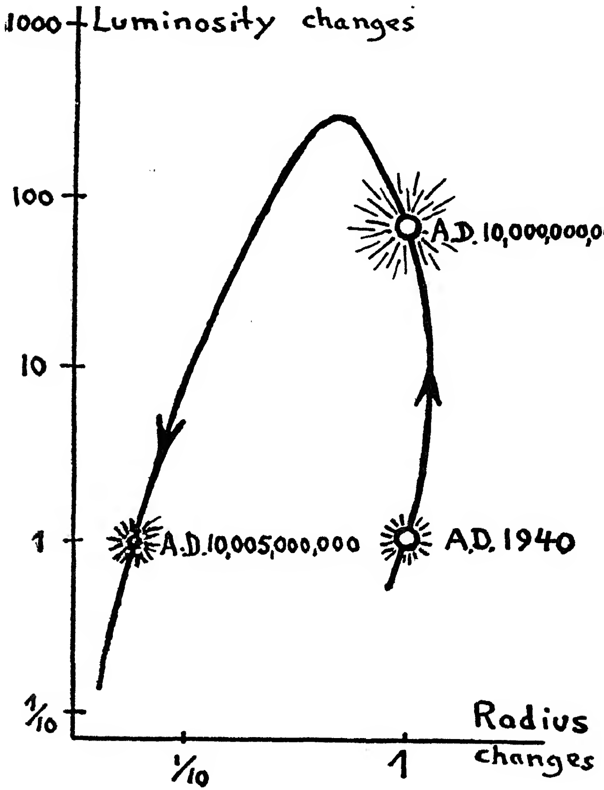


FIGURE 31
The evolution of the Sun. After passing through a stage of extremely high luminosity, the Sun begins a rapid contraction accompanied by declining light emission.

ture of our earth so slowly that during the whole geological period, while the Sun lost only about one percent of its hydrogen content, the earth's temperature rose by barely a

few degrees. Thus, it is not a sudden cosmic catastrophe we are expecting as a consequence of thermonuclear processes in the Sun (see Chapter IX), but a condition that can be foreseen in time and possibly avoided by the colonization of Neptune, for example.

The slow rise in temperature will, however, most probably be accompanied by such evolutionary changes in the biological world that terrestrial life will become more and more adapted to increasing heat. But since no highly developed organism can live in boiling water, as conditions become more and more unfavourable for life the biological species will most probably begin to degenerate. It is, therefore, quite probable that the higher species will have vanished long before the temperature becomes really intolerable; and the last radiation efforts of the aged Sun will be "observed" only by the simplest and most stable of micro-organisms.

WHAT THEN?

As we have seen in a previous section, it is possible to construct a heating-machine that gives more heat the less fuel it has. But there is surely no mechanism that could give off heat without any fuel at all; and, as soon as the Sun completely consumes the last of its hydrogen, it will no longer have any subatomic energy sources left. Deprived of the resources that will have kept it going for ten billion years, our Sun will be forced to go back to an earlier energy-producing mechanism out of favour for all that long period of time.

The Sun will begin to contract again. But, as we have seen, gravitational energy is practically as nothing compared to the wealth of energy supplied by nuclear reac-

tions, and the Sun's progressive collapse will have to proceed at a pretty fast rate after the splendid life it has led on subatomic energy sources. From that point on our Sun will be shrinking rapidly in size; after a while its luminosity will also begin to diminish. Rapidly retreating to its present luminosity—and here rapidly means, of course, in a few million years!*—the Sun's radiation will sink lower and lower as it approaches its ultimate stage of thermal death. These dying stages of solar evolution will be discussed in more detail in one of the following chapters.

* On the descending part of its evolutionary track the Sun will also have a much smaller radius than at its present stage, as can be readily seen from Figure 31.

The Sun among the Stars

HOW BRIGHT ARE THE STARS?

IN THE long ago days of childhood many of us perhaps believed that the stars were only little silver lanterns attached to the blue firmament above our heads. This oldest and simplest of all hypotheses often came nostalgically back to the author's mind when, during his researches on the sources of stellar radiation, he encountered so many seemingly unsurpassable difficulties. But unfortunately he could not doubt that this good old theory is incorrect, and that the stars are actually giant masses of extremely hot gas very similar to our Sun. The tremendously great distances separating us from these remote suns make them look small and faint, but astronomical observations permit us to estimate these interstellar distances and to compare the *actual* (or *absolute*) *luminosities* of different stars with the luminosity of our own Sun.

Let us take, for example, the brilliant eye of the Great Dog. The Great Dog is, of course, a constellation to which this name was given by ancient astronomers in the course of their attempts to mark off different groups of bright stars by identifying them with animals or mythological persons. Though to the modern prosaic eye the combination of stars forming this particular constellation (Figure 32) hardly resembles any known breed of dog, or any animal whatsoever, one must have respect for the classics. The eye

of this stellar dog is the brightest star seen in the sky and is well known under the name of Sirius. Astronomers tell us that it is about 500,000 times farther from us than is our Sun—52,000,000,000,000 miles away!—and that, if it were

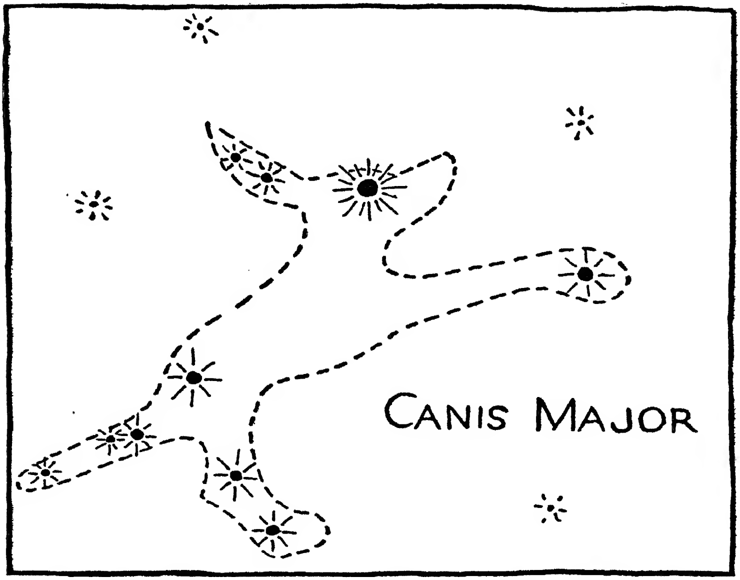


FIGURE 32
The constellation of the Great Dog.

at the Sun's distance from us, Sirius would give us 40 times more light and heat than does the Sun.

There are much more luminous stars, as for example Y Cygni,* which is 30,000 times brighter than our Sun, but not very conspicuous visually because of its exceedingly great distance. On the other hand, there is no lack of much fainter stars, as for example Krueger 60 B† (not all stars

* In the constellation of the Swan.

† The B-component of the sixtieth star registered in Krueger's catalogue.

have such elegant names as Sirius), with an absolute luminosity (or total radiation) 1000 times smaller than the Sun's. If we compare our Sun's luminosity with that of all other known stars, we find that it occupies a more or less intermediate position among them and represents in this sense *a typical average star.*

THE COLOUR OF STARS AND SPECTRAL CLASSES

In the study of the physical properties of stars, it is very important to know, not only their absolute luminosities, but also the spectral composition of the emitted light, which permits us to determine the surface temperatures of these remote bodies. We have seen in Chapter I that the surface temperature of the Sun can easily be estimated from the amount of radiation emitted by each unit of its surface. In the case of most stars, however, we are unable to make direct measurements of their surface areas because, owing to their very great distances, they look like dimensionless luminous points even through the most powerful telescopes.*

Fortunately there are a number of other characteristic properties of the radiation emitted by hot bodies which enable us to estimate stellar temperatures even when we do not know their surface brightness. We know that all bodies when subjected to steadily increasing heat first emit a rather reddish radiation, which changes into a yellowish, then into a whitish, and finally into a bluish one as the temperature rises higher and higher. These colour changes of the emitted light are due to changes of relative intensity in the different parts of the emission spectrum in response

* Only in a few cases of very near and large stars can such direct measurements of stellar diameters be carried out by means of an ingenious interferometric method proposed by A. Michelson.

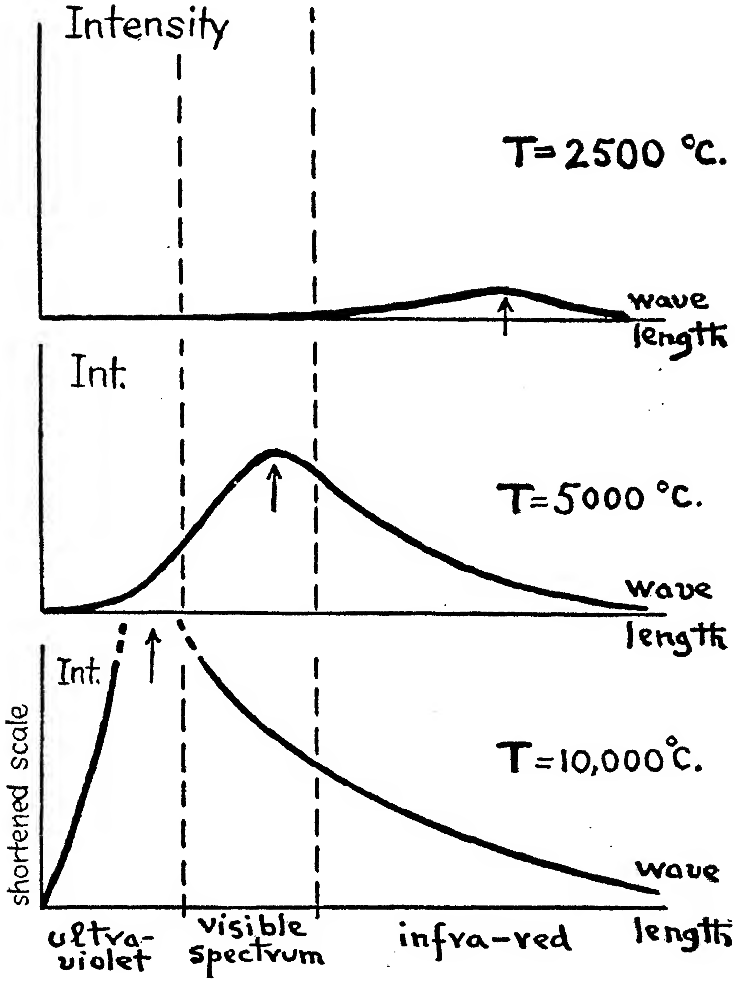


FIGURE 33
The continuous emission-spectrum changes with the temperature (T).

to changes in the temperature. As may be seen from Figure 33, the maximum of light emission shifts gradually from the red to the violet part of the spectrum as the temperature rises. Thus, by comparing the colour of the light emitted by different stars, we can form a very good idea of their relative surface temperatures and can say that reddish stars are comparatively cool, whereas bluish ones are very hot.

A still more sensitive method for estimating stellar temperatures depends on the study of the relative intensities of the numerous dark thin lines (so-called *Fraunhofer lines*) that intersect the continuous emission spectra of different stars, including our Sun. These dark lines are due to the selective absorption of light by the stellar atmospheres. As the relative absorbing power of different atoms depends, to a very high degree, on the temperature, the appearance of this absorption-line pattern changes very markedly from star to star and permits us to estimate their respective surface temperatures simply by a glance at the character of the spectrum.*

In astronomical practice, it is customary to divide the observed range of stellar temperatures into ten groups, which are known as the *Harvard spectral classes* and are reproduced in Plate VII. The ten classes of this system are called by different letters, which, evidently in order to mislead the layman, are not arranged in alphabetical sequence. There is, however, a simple mnemonic sentence, known to all English-speaking astronomers, which will help us not to get mixed up in this mess of absorption

* The theory that gives the exact relation between the temperature of the absorbing gas and the character of the absorption spectrum was first worked out, on the basis of the quantum theory of atomic structure, by the Indian astrophysicist Meh-Nad-Saha.

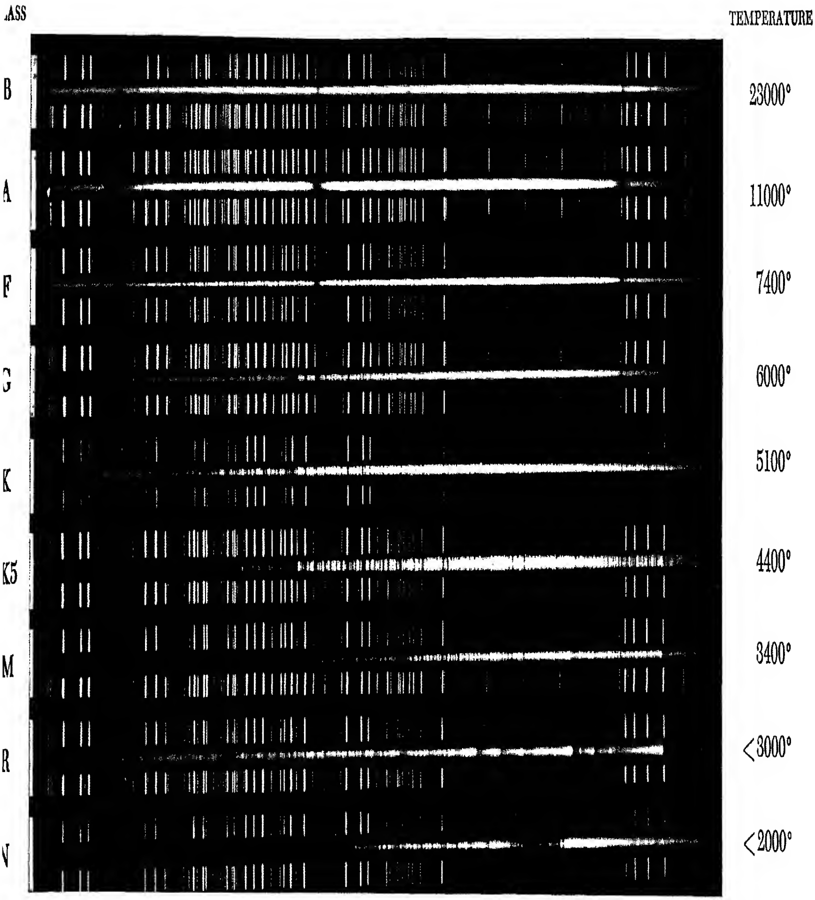
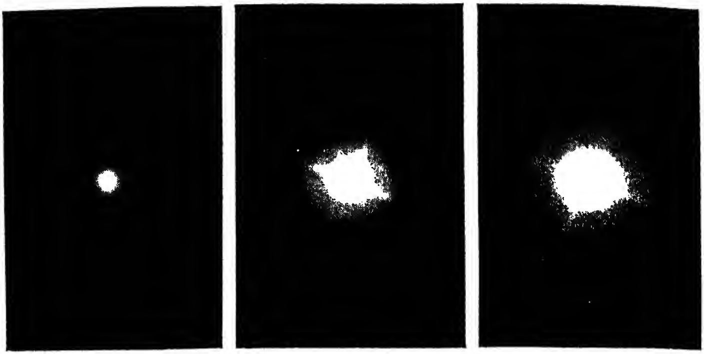
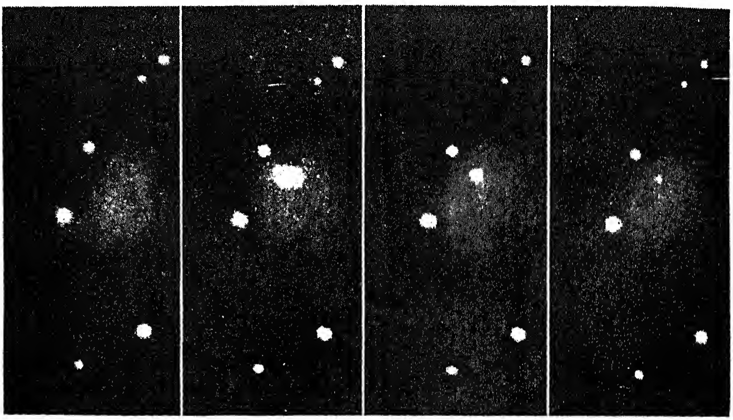


PLATE VII. The Harvard spectral classification of stars. The differences in the spectra permit astronomers to estimate the surface temperatures. (See p. 126.)



A. Expanding nebulous ring about Nova Aquilæ 1918. Photographs taken on July 20, 1922, September 3, 1926, and August 14, 1931. (See p. 176.) (Mt. Wilson photograph.)



B. Appearance and fading of the supernova in I.C. 4182. Photographs taken on April 10, August 26, December 31, 1937, and June 8, 1938. (See p. 183.)
(Photographed by Dr. F. Zwicky.)

PLATE VIII. NOVA AND SUPERNOVA

lines. It reads: "Oh, Be A Fine Girl, Kiss Me Right Now . . ." As to whether S, the last letter, stands for "Sweetheart" or for "Smack," there is a long-standing, still unconcluded dispute between the Harvard and the Yerkes astronomers.*

If the spectrum of a given star falls, according to its properties, somewhere in between two of the above classes, a decimal notation is used, e.g., A2 = two-tenths the distance from A to F, or K5 = five-tenths the distance from K to M (see Plate VII). In this Harvard classification our Sun belongs to the class G (6000 degrees), Sirius to the class A (11,200 degrees), and the faint star Krueger 60 B to the "cold" class M (3300 degrees).

Knowing the star's surface temperature as given by its spectral class, we can now estimate also its geometrical dimensions by comparing the surface brightness that should correspond to this temperature with the star's absolute luminosity. We find in this way that the diameters of Sirius and Y Cygni are respectively 1.8 and 5.9 times larger than our Sun's, whereas the faint star Krueger 60 B has a diameter half as long.

THE RUSSELL DIAGRAM

When we compare these four stars (including the Sun) we may easily notice a very interesting regularity in the fact that stars of higher luminosity generally possess higher surface temperatures and larger radii. A more detailed study of this relationship has led to a remarkable classification of stars, which represents at the present time the most important basis for theories of stellar properties and evolution.

* Plate VII does not show the spectra for classes O and S.

The first weeks of March of the year 1913 turned out to be a very unfavourable period for astronomical observation at Princeton. It was raining most of the time, and the overcast skies absolutely excluded any kind of observatory work. But this did not much disturb Professor H. N. Russell, director of the observatory, who was even glad that his enforced idleness was enabling him to bring some order out of his previous observations and to check certain ideas that had been preoccupying his mind for the last few months.

On a large sheet of millimetre-paper, Russell began to construct a diagram to represent the relations between the absolute luminosities and the spectral classes of all the stars for which he had these data. It was rather tedious work, for many hundreds of stars had to be plotted on the diagram, but, as he approached the end of it, the pattern formed by the points began to take on a very interesting and peculiar shape (Figure 34).

Clear across the diagram, from its lower right-hand to its upper left-hand corner, ran a narrow band that contained most of the plotted points and, in particular, the point representing our own Sun. All the stars belonging to this *main sequence* are evidently closely related and differ by only one factor, presumably their mass. These "normal stars" range continuously from the comparatively cool and faint *"red dwarfs"* up to the brilliantly blue and luminous *"blue giants."*

But this marked regularity was broken by a number of striking exceptions, which, however, as the phrase goes, helped to prove the rule. There were two distinctly different types of stars falling far from the main sequence. A number of points were scattered rather irregularly in the

upper right-hand corner of the diagram, and these corresponded to the stars possessing extremely high absolute

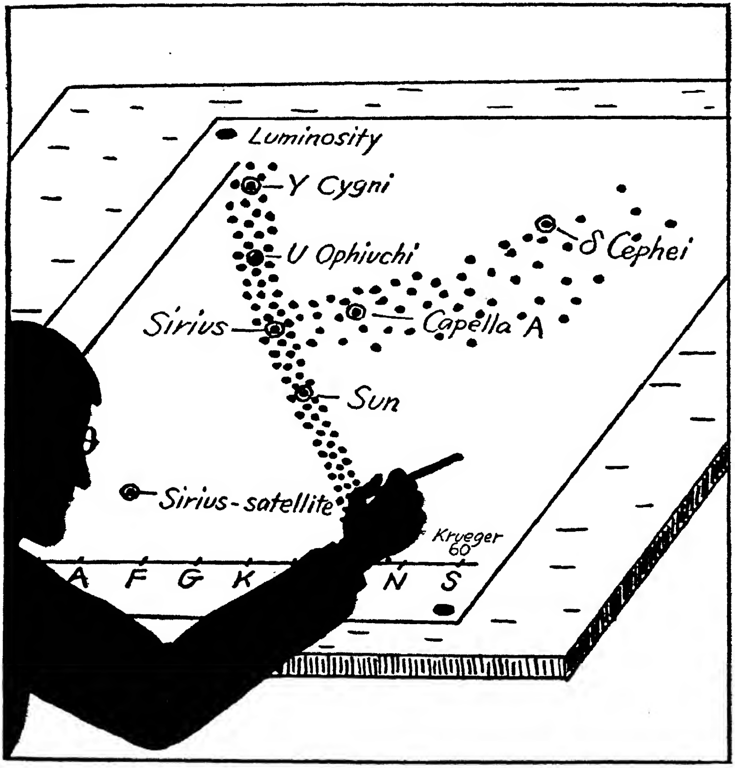


FIGURE 34
. . . the pattern formed by the points began to take on a very interesting and peculiar shape (the Russell diagram).

luminosities in spite of their comparatively low surface temperatures. Since low surface temperature means a rather small intensity of light per surface unit, the high

total luminosities can be understood only on the supposition that they have extremely large geometrical dimen-

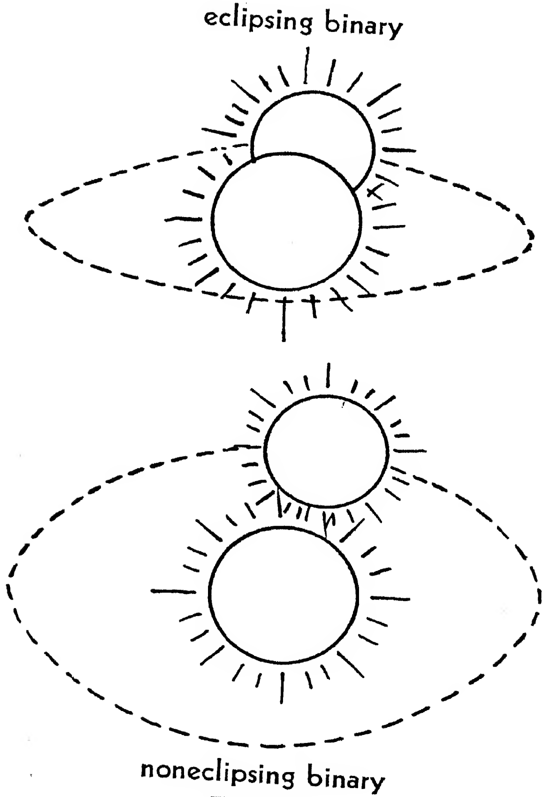


FIGURE 35
Double stars. If the orbital plane of the two components is sufficiently inclined, the star system becomes an eclipsing variable.

sions. These bodies have received the name of *red giants,* and include in their number such well-known stars as Capella and the *cepheid variables* (see p. 177).

The lower left-hand corner of the Russell diagram was occupied by the second class of abnormal stars, known as *white dwarfs.* The high surface temperatures together with the small total luminosities of these stellar bodies definitely indicates their very small geometrical dimensions, which, as we shall see later, are only a few times larger than the dimensions of the earth.

We shall leave the discussion of both these classes of "abnormal" stars to the following two chapters, and shall now concentrate our attention only on the normal stars of the main sequence.

STELLAR MASSES

Knowledge of the stellar masses represents one of the most important, but also one of the weakest points of observational astronomy. The only way to estimate the mass of a star is to observe the motion of some other body revolving around it; thus, for example, the period of the rotation of the earth around the Sun permits us to estimate the mass of the central body of our system. Although the possibility is not excluded that most of the other stars possess planetary systems analogous to our own (see Chapter X), their great distances will not permit us to see them.

Fortunately there are a considerable number of stars that "live in couples," forming the so-called *binary,* or *double-star systems* (Figure 35). In such cases the relative motions of the two components of the system may be directly observed, and their respective masses can then be estimated from the rotation periods.* But since an esti-

* From the observational point of view the double-star systems could be divided into the *visual binaries,* seen separately through strong telescopes, and the *spectroscopic binaries,* the relative motions of which can be observed only through the *Doppler effect* on the lines in their spectra.

mate of mass requires a complete knowledge of all the elements of motion, there are at present only several dozen stars for which the masses are known with sufficient certainty. These few data are enough, however, to allow us to arrive at some very interesting conclusions concerning the relation between stellar masses and luminosities.

It was indicated first by Sir Arthur Eddington that *the luminosities of stars are a definite function of their mass, increasing very rapidly with the increase of mass.* Taking, for example, the stars that have already been discussed, we find that the highly luminous Y Cygni (with a luminosity 30,000 times that of the Sun) is 17 times heavier than the Sun; that Sirius (with 40 times the Sun's luminosity) is only 2.4 times heavier; and that the faint star Krueger 60 B (with .001 times the Sun's luminosity) has but one-tenth the solar mass.

As the total radiation of stars increases much more rapidly than their mass, the energy production per gramme of matter must be much greater in heavy stars than in light ones. From the above figures we see that the energy production per unit mass in Y Cygni, Sirius, and Krueger 60 B is respectively 1800, 15, and 0.005, relative to that of the Sun. But if the energy generation in all stars comes from thermonuclear reactions, as it does in our Sun, the different rates of energy liberation must be due to different physical conditions existing in their interiors, and chiefly to differences in their central temperatures.

NUCLEAR REACTIONS IN STARS

We have seen in Chapter I that Eddington's ingenious analysis of the equilibrium conditions of giant gas-spheres permits us to understand the different physical properties

of the Sun's matter at different depths from its surface, and to arrive at definite conclusions concerning the density and temperature in its internal energy-producing region. The same method, which proved so successful in the case of the Sun, can also be applied to the study of the internal conditions of other stars. In fact, knowing the mass, the radius (or the surface temperature), and the total radiation of a given star, we can, by way of rather complicated calculations, arrive at the values of its central temperature and density. The results of such analysis, as applied to the typical stars we have discussed above, are given in the following table, which also includes their energy production per gramme of stellar material as estimated from the observed absolute luminosities and masses.

STAR	MASS (*relative to Sun*)	CENTRAL DENSITY (*relative to water*)	CENTRAL TEMPERATURE (*degrees C.*)	ENERGY PRODUCTION PER UNIT MASS $\left(\frac{erg}{gm.\ sec.}\right)$
Krueger 60 B	0.1	140	14×10^6	0.01
Sun	1.0	75	20×10^6	2
Sirius	2.4	41	25×10^6	30
Y Cygni	17.0	6.5	32×10^6	3600

The last two columns of this table make clear the tremendous effects of temperature on the observed energy production. *An increase of the temperature in the stellar interior from 20 million to only 32 million degrees, is accompanied by an increase of the energy production per*

unit mass by a factor of 1800. But this is just what we should expect in the case of thermonuclear reactions, the rates of which, as we have already seen, usually increase proportionally to a very high power of the temperature.

We have seen in the previous chapter that the energy production of our Sun is due entirely to the self-regenerative carbon-nitrogen reaction cycle, in which the hydrogen of the solar matter is steadily transformed into helium. It is natural to assume that *the same reaction cycle is also responsible for the energy production in all other stars of the main sequence.* The calculations do, in fact, show that the amounts of energy that would be set free by this thermonuclear reaction cycle, at the temperatures and densities obtaining inside the stars shown in the table, correspond very closely with their observed luminosities. *Thus, the normal stars, like our own Sun, are living on the subatomic energy liberated in the process of the transformation of hydrogen into helium.*

A COMPETING REACTION IN THE LIGHTER STARS

It should be pointed out, however, that, although the carbon-nitrogen cycle is of primary significance for most of the stars in the main sequence, it has a rather important competitor in the case of the comparatively light stellar bodies, such as Krueger 60 B. The central temperatures of these "cool" stars are relatively low, and the slow thermal protons experience difficulty in penetrating such heavy nuclei as those of carbon or nitrogen. Under these conditions it is necessary to take into account the possibility of a quite different nuclear reaction, one that takes place between protons themselves and does not need the catalysing action of any heavier element. This different

reaction, first studied by the young American physicist Charles Critchfield, consists of *the formation of a heavy-hydrogen nucleus, or a deuteron* (see Chapters II and III), *in the collision between two thermal protons.* It can be written in the form:

$$_1H^1 + {}_1H^1 \longrightarrow {}_1D^2 + \overset{+}{e} \text{ (positive electron)}$$

and is usually followed by the transformation of the new-born deuterium nuclei into the heavier nuclei of helium:

$$_1D^2 + {}_1H^1 \longrightarrow {}_2He^3 + \text{radiation, etc.*}$$

Exact calculations show that at temperatures as low as 15 million degrees this reaction is just as important as the carbon-nitrogen cycle, and that, at still lower temperatures, it becomes of primary importance. Thus, for very light and faint stars of the main sequence, possessing central temperatures at or below 15 million degrees, the mechanism of energy production is slightly different than it is for their more brilliant relatives, such as our Sun or Sirius.

STELLAR EVOLUTION

It was mentioned in the previous chapter that the author's study of the future evolution of our Sun leads to the surprising conclusion that its temperature and total radiation are bound to increase while its hydrogen content diminishes. In the frame of the Russell diagram this means that the point representing the Sun is slowly moving upward and leftward from its present position toward that of the hotter and more luminous stars.

The results of such calculations are shown in Figure 36,

* "Etc." is here an indication of the fact that this reaction is followed by a series of numerous and complicated reactions eventuating in normal helium $_2He^4$.

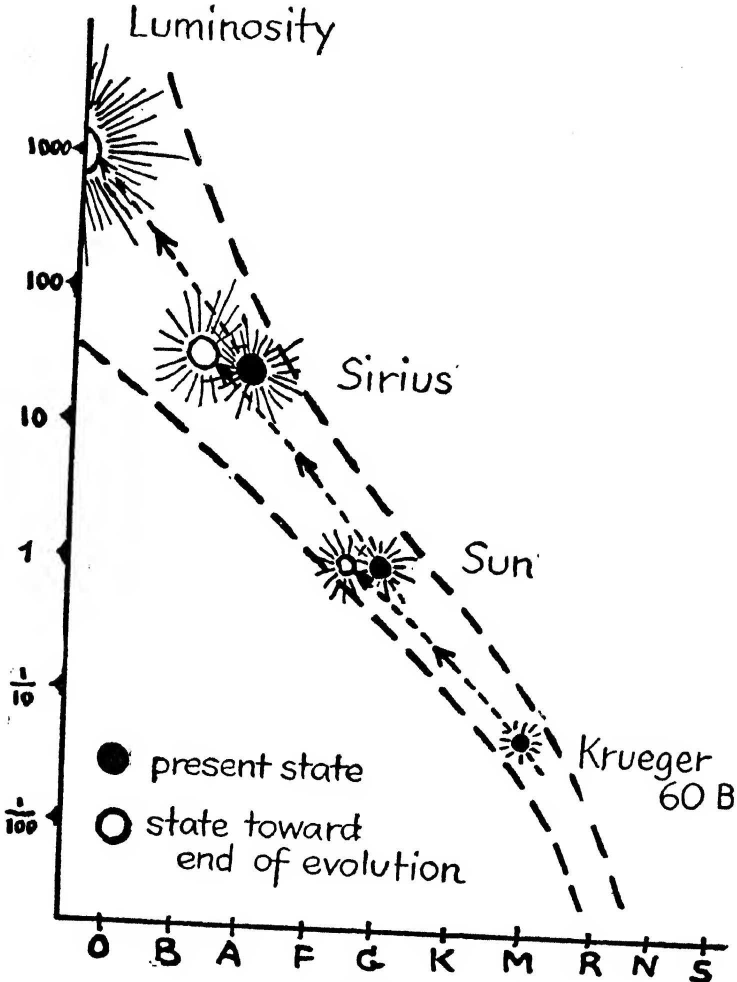


FIGURE 36
Future changes in the luminosity and spectral class of three stars, according to the theory of stellar evolution.

which represents the evolutionary tracks of our Sun and two other stars (Sirius and Krueger 60 B) of the main sequence. We see that the track of stellar evolution runs more or less up along the main sequence of stars, and begins to bend toward the lower luminosities only after the original radiation has increased by a factor of 100. Thus, after 10 billions of years, our Sun will become as brilliant as Sirius is now, while Sirius itself will be approaching a luminosity comparable to the present state of U Ophiuchi.

This does not mean, however, that the stellar sky of, let us say, A.D. 10,000,001,940 will necessarily be more luminous than the sky of A.D. 1940. For, whereas some of the stars will gain considerably in luminosity, many others, which are already of age now, will have exhausted their remaining hydrogen resources and will be declining into obscurity. In this sense the migration of stars on the Russell diagram is rather analogous to the age changes taking place in a human society, where the places of the old and dying are constantly being taken by the growing younger generations. But just as, in the case of human society, secular changes in the population can be produced by such factors as a falling birth rate, so stellar society can be strongly affected by factors governing the formation of new stars. If, as is very probable (see Chapter XII), the "stellar birth rate" is falling with the increasing age of the world, we must face the possibility that the general picture of the sky will change as the universe grows older.

It needs to be said here that stars with different masses will run through their evolutionary lives at different speeds. Heavier, and therefore more luminous, stars will use up their hydrogen supply much faster than the lighter ones.

Thus, if two stars of different mass have started life simultaneously with equal proportions of hydrogen, the heavier one will be dying when the lighter one will still be in the ascending stage of its evolution. Sirius, for example, burning up its fuel 15 times faster than the Sun, will begin to end its life 15 times sooner; and the most brilliant stars of the main sequence (the blue giants) can hardly expect to live more than several millions of years.

STELLAR EVOLUTION AND THE MASS-LUMINOSITY RELATION

In this connexion a very important objection could be put forward by an attentive reader who has followed carefully the exposition of the present chapter.

"It was indicated above," he might say, "that there is a definite empirical relation between the luminosities of different stars and their respective masses. But if, during the course of evolution, each star changes its luminosity by as much as a factor of 100, we should be able to find stars of equal mass but different luminosities, or stars greatly differing in mass but having the same luminosity. Does not the empirical mass-luminosity relation, as established by Eddington, contradict this view of stellar evolution?"

In order to escape from this seeming dilemma we shall first have to pay more attention to the speed at which the evolving star passes through the different stages of its evolution; for if it should turn out that most stars are in the same evolutionary stage, our problem will be solved. We have already seen that the energy-producing plant in the stellar interior has the peculiar property of burning faster when less fuel is left. Thus, whereas in the lower part of

the evolutionary track the star uses its hydrogen fuel very sparingly, the consumption becomes much higher toward the later stages. The high luminosities characteristic of these later stages naturally require much higher rates of subatomic energy liberation and a correspondingly higher consumption of hydrogen. It follows that the star spends a considerably longer time in the lower stage of evolution, and runs through the later stages with comparative rapidity.

The calculations show, for example, that our Sun will spend about 90 percent of its life in the first half of its evolutionary track (luminosity increase by a factor of 10) and only 10 percent in the remaining half (luminosity increase from 10 to 100). Consequently, there is a much greater chance of finding an arbitrarily chosen star in the beginning of its evolutionary track than at the end of it. In the same way, in an odd society where childhood took up 90 percent of the total life of every individual, we should expect to find an almost exclusively child population. Thus, only a few of the stars that were used for the construction of the mass-luminosity curve would show marked deviations from the smooth curve, and, as a matter of fact, several such deviations (in the direction of too large luminosities) are actually observed.

The second reason we find most of the investigated stars in the same stage of their evolution lies in the fact that *the stellar universe is still very young.* It will take about 10 billion years more for our Sun completely to burn up its fuel and come to the end of its hydrogen evolution. On the other hand, there are definite indications (see Chapters XI and XII) that the whole stellar universe was formed not more than 2 billion years ago. It is clear

that during this "short" period the stars comparable in their intensities to our Sun could not have evolved to any considerable degree. Only much brighter, and consequently much faster-living, stars from the upper part of the main sequence could have experienced such considerable changes since the epoch of their formation, and it is precisely in this region that the striking deviations from the mass-luminosity relation are actually found.

THE YOUTH AND OLD AGE OF STARS

We have thus far considered only that part of stellar evolution which is determined by hydrogen consumption in the nuclear reactions produced by high temperatures. But what of the state of the star before its central temperature reached the value of 20 million degrees necessary for the beginning of the carbon-nitrogen reaction cycle? And what happens to a star after all its original hydrogen content has been used up and no more subatomic energy is available? Can one find in the sky samples of stars that are still in their babyhood or, on the other hand, already in their very old age?

These questions remind us of the existence of the two "abnormal" classes of stars which definitely did not fit into the normal scheme of hydrogen evolution—the red giants and the white dwarfs. Let us, then, concentrate our attention on these possible representatives of infancy and senility.

Red Giants and the Youth of the Sun

SOME TYPICAL RED GIANTS

WE HAVE seen that the so-called *red giants* are stars of extremely large dimensions and very low surface temperatures. A typical representative of this peculiar class of stars can be found, for example, in Capella (or α Aurigæ), a star that is probably familiar to those readers who are interested in the night sky. Telescopic observations reveal that Capella actually represents a double-star system, whose two components revolve rather closely around each other.

The fainter component of the system (known as Capella B) is a normal star of the main sequence. But the brighter and larger star (Capella A) has rather unusual properties as compared with the multitude of other stars. The diameter of this giant is 10 times larger than the solar diameter, and its radiation surpasses that of our Sun by a factor of 100. For a normal star of the main sequence that possessed such high luminosity we should also expect a very high surface temperature; but observations show that Capella A is in about the same spectral class as our Sun, that is, it is much redder than it should be.

In Figure 37, representing the upper right-hand corner of the Russell diagram, we see that this star falls well away from the main sequence and may be considered a typical red giant.* The estimates of its mass (from the relative

* In the case of Capella A the radiation is not yet quite red but rather

motion of the two stars forming the system) give a value of only 4 times the mass of the Sun, so that *the average density of Capella A must be 250 times less than the density of solar matter,* or 0.005 times that of water. These low

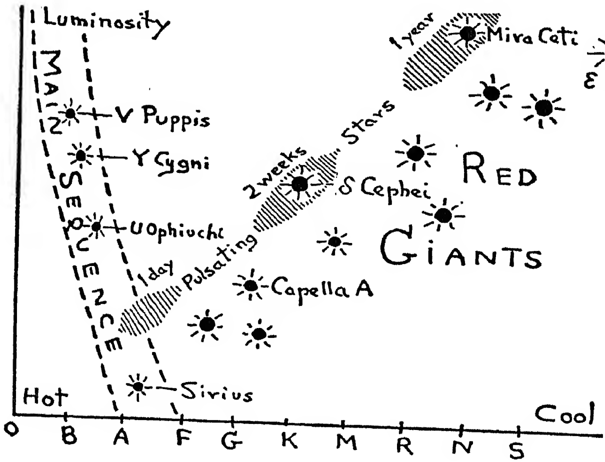


FIGURE 37

The upper part of the Russell diagram, showing the position of the red giants and the region of pulsating stars.

densities are characteristic of the red giants and represent much more dilute states of matter than the normal stars of the main sequence.

A still more typical example of the red giants is another star belonging to the same constellation as Capella itself, ζ Aurigæ K, which has a mass of about 15 Sun masses, but a diameter surpassing that of the Sun by a factor of 160, and therefore *an average density only 0.000,005 that of water.** Although 56 times more luminous than Capella A,

yellowish. It is, however, much *redder* than a normal star of such high luminosity would be.

* In the central regions of this star, the density reaches the value 0.000,14.

this star belongs to the cold spectral class M and looks quite red as compared with other stars.

But the most striking cases of cold giant stars was revealed by recent observations at the Yerkes Observatory of

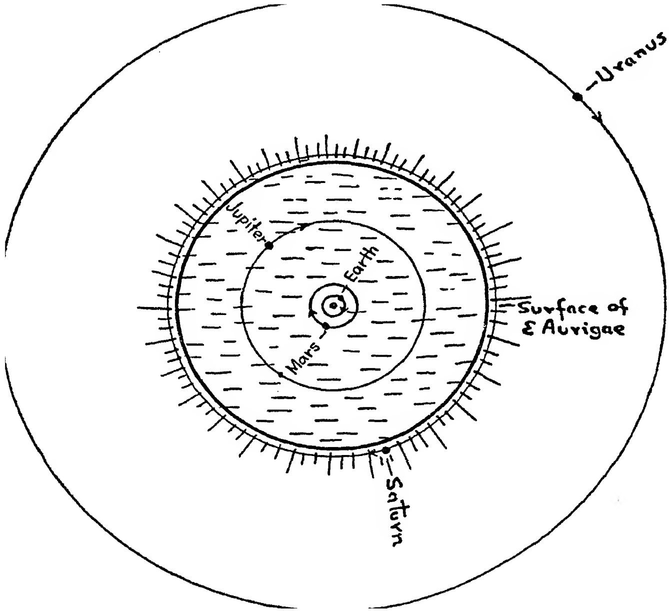


FIGURE 38
The relative sizes of ε Aurigæ I and the solar system.

ε Aurigæ (no, the red giants have no preference for the constellation Auriga; nor has the author any preference for this particular constellation in selecting his examples; it is only pure coincidence). These observations indicated that the star is actually a binary system, and that one of the

components (ε Aurigæ I) is so large and so cool that the radiation it emits is mostly *infrared* (hence the I in its notation). There is no provision in the old Harvard spectral classification for stars of such exceedingly low temperatures (1700 degrees), and we might simply call it "Class I."

Although the mass of this star is only 25 times larger than the solar mass, its diameter surpasses that of the Sun by a factor of 2000. This star is so large that almost our entire planetary system, including the orbits of Jupiter and Saturn, could be placed inside it, with only Neptune and Uranus sticking out (Figure 38). The mean density corresponding to such dimensions is only 0.000,000,003 relative to water!

But it should be noted that we speak only of mean densities. In any gaseous body, the density increases as we approach the central regions, and it has been shown, particularly in the case of the red giants, that this density increase is especially large.

INSIDE THE RED GIANTS

In order to ascertain the physical conditions obtaining in the interior of the red giants, we can apply the same method we used in the case of the Sun and the other stars of the main sequence. Starting from directly observable conditions on the surface, we can proceed step by step into the deeper regions of the star, and finally arrive at values for temperature, density, and pressure near the stellar centre.

This analysis will demonstrate that, although the central temperatures of red giants are much higher than their surface temperatures, they are still considerably lower than

the central temperatures of our Sun and the other normal stars. In the case of Capella A, for example, we get a value of 5 million degrees (compared with the solar temperature of 20 millions), and for ζ Aurigæ K only 1.2 millions. The central temperature of the giant rarefied star ε Aurigæ I is probably considerably lower than one million degrees.

Of course, from a terrestrial point of view, the interior of these stars is still very hot, but only very few thermonuclear reactions could go on at such temperatures. In particular, Bethe's carbon-nitrogen cycle, which supplies the energy for our Sun and other normal stars, would be practically stopped by such a "nuclear frost" and would lead to hardly any energy liberation at all. The same pertains to Critchfield's deuteron-formation process.

In order to find suitable subatomic energy sources for these comparatively cool stars, we must look for nuclear transformation processes which would go on at much lower temperatures than do the two above. The study of this problem was undertaken in 1939 by the author of this book and his colleague Dr. Edward Teller, with results that seem to give us a satisfactory explanation of the riddle of energy-production in red giants.

THE REACTIONS OF LIGHT ELEMENTS

As we have seen, the easiest reactions to start are those between protons and the nuclei of the lightest elements of the periodic system.* The following six reactions are a complete list of all the possible nuclear transformations that involve the elements lighter than carbon and nitrogen:

* This does not include the proton-proton reaction leading to deuteron formation, which is comparatively slow owing to the small probability of electron emission.

(1) $_1D^2 + {_1H^1} \longrightarrow {_2He^3}$ + radiation
(2) $_3Li^6 + {_1H^1} \longrightarrow {_2He^4} + {_2He^3}$
(3) $_3Li^7 + {_1H^1} \longrightarrow {_2He^4} + {_2He^4}$
(4) $_4Be^9 + {_1H^1} \longrightarrow {_3Li^6} + {_2He^4}$
(5) $_5B^{10} + {_1H^1} \longrightarrow {_6C^{11}}$ + radiation
(6) $_5B^{11} + {_1H^1} \longrightarrow {_2He^4} + {_2He^4} + {_2He^4}$

The available data of nuclear physics permit us to estimate the rate of subatomic energy liberation for each of the above reactions with the result that *they fall into three distinctly separate types.*

The first type includes only the extremely rapid reactions between deuterons and protons (1). Owing to the small electric charges of both particles involved, this reaction leads to a very high energy liberation even at such low temperatures as a million degrees.

The second type contains the slower reactions of both lithium isotopes (2, 3), the reaction of beryllium (4), and the reaction of the heavier isotope of boron (6). The temperatures necessary for these reactions lie in the range between 3 and 7 million degrees.

Finally, the third type consists of the still slower reaction of the lighter isotope of boron (5), which requires a temperature only slightly lower than that to be found in the centres of the main-sequence stars. The reason for so comparatively low a rate in this particular case is that the transformation involves the process of a γ-ray emission, which causes a considerable decrease of its probability. In fact, it is well known that the emission of γ-rays is as a rule many millions of times less probable than the ejection of a nuclear particle, so that in order to obtain an appreciable rate for that kind of reaction it is necessary to intensify the bombardment by raising the temperature of the gas.*

* The reader may have noticed that the first reaction on our list (D-H)

THE ABSENCE OF THE LIGHTEST ELEMENTS IN THE SUN

Since the liberation of energy through the three types of reactions discussed above begins at a comparatively low temperature, we should expect that, at the central solar temperature of 20 million degrees, the subatomic energy would flow out at quite fantastic rates. Indeed, if, with the present temperature, there were any appreciable amounts of the lightest elements in the solar interior, the liberated energy would cause a terrific explosion of the Sun. We must conclude, therefore, that *these "dangerous" elements are absent from the solar interior, and that, if there were any in the earlier stages of evolution, the Sun must have exhausted them completely in that distant period of its history when its central temperature was much lower than it is now.*

The analysis of the solar spectrum does seem to indicate, however, that a certain small amount of lithium, beryllium, and possibly boron is still present in the solar *atmosphere.* The presence of these elements in the earth also suggests that they must have been present, at least in the outer layers of the Sun, at the time when our globe was separated from the central body. But even on earth these lightest elements are relatively scarce (as may be seen from Figure 39), and this supports the conclusion that they disappeared early in the history of the world.

Incidentally, these differences in chemical composition between the interior and the outer envelope of our Sun

also involves γ-ray emission and yet is the fastest of them all. The point is, however, that in this case the high penetrability of the nuclear barrier, due to the small electric charges, overcompensates for the low probabilities of γ-ray emission. If the D-H reaction could go on without radiation, it would be millions of times more probable than it actually is.

and other stars are of great importance for the problem of the origin of chemical elements and for questions concerning the early stages of the development of the universe.

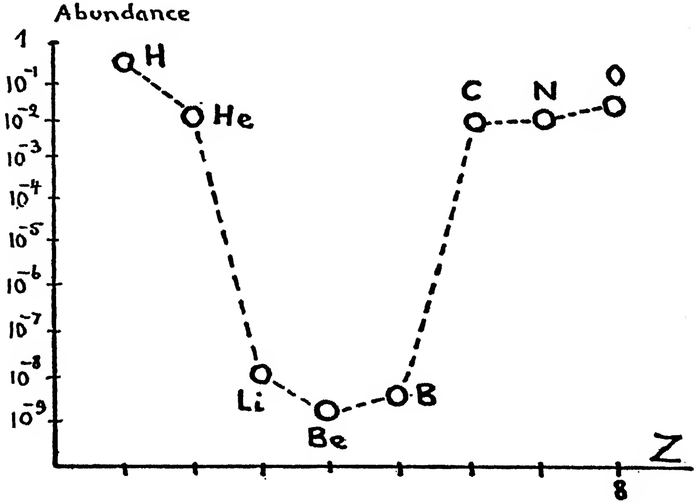


FIGURE 39
The relative abundance of the lightest elements in the earth's crust, showing the extremely small amounts of lithium, beryllium, and boron. Approximately the same curve has been found to hold for the meteorites and for stellar atmospheres.

THE REACTIONS OF LIGHT ELEMENTS IN RED GIANTS

We shall now return to our original problem concerning the energy sources of red giants. From the discussion above we have seen that the thermonuclear reactions between hydrogen and the other lightest elements occur between temperatures of a million and 20 million degrees, which limits coincide with the estimated range of the central tem-

peratures of various red-giant stars. It is natural, therefore, to conclude that these stars are still "burning" their supplies of those light elements that were exhausted by our Sun a long time ago. The calculations show, in fact, that the presence of only a small percentage of these elements in the central regions of red giants would suffice to supply the energy of their observed radiation.

Since, however, the central temperatures in different stars of this class exhibit a great range, we must choose different reactions to account for particular cases. For example, the coolest red giants, such as ε Aurigæ I and its extreme neighbours in the Russell diagram, must live exclusively on the deuterium-hydrogen reaction, and their lithium, beryllium, and boron supplies must be as yet untouched. Such stars as Capella A and ζ Aurigæ, on the other hand, have evidently already exhausted their deuterium supply, and are using up the elements of the second reaction type mentioned above. Finally, the red giants that fall close to the main sequence in the frame of the Russell diagram must be using for their energy production the boron isotope $_5B^{10}$, and are getting ready to join the family of normal stars as soon as their light nuclear fuel comes to an end.

Figure 40 gives a schematic presentation of the different parts of the Russell diagram in terms of the specific nuclear reactions that are of predominant importance in them. We see that, whereas the main sequence, with the exception of its lower part,* corresponds to one definite mode of energy production (the carbon-nitrogen cycle), the region of red giants includes a variety of stars that use different fuels in their furnaces. The parts corresponding to different light-

* See p. 135 above.

element reactions may often overlap, so that we may find stars in which two, or even three, elements are equally important for energy production.

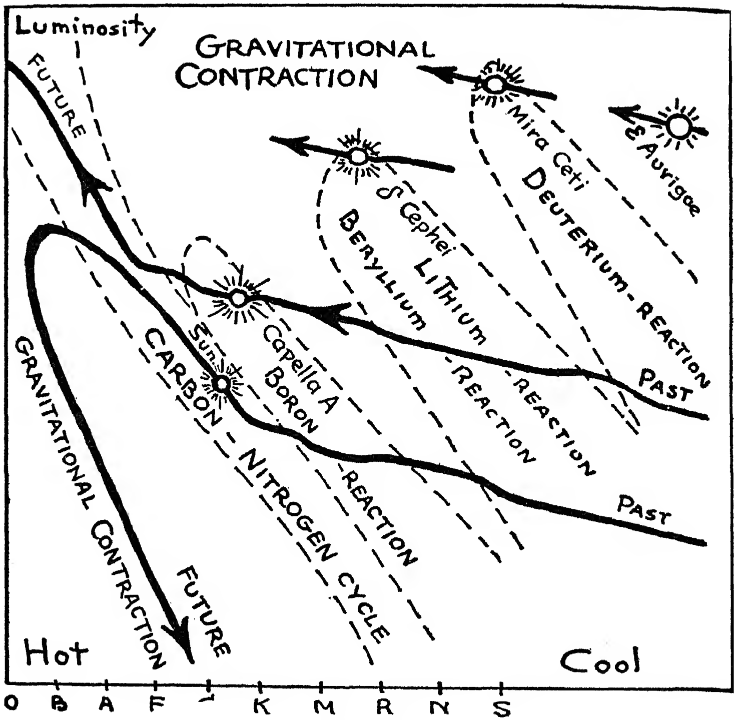


FIGURE 40
The regions of different nuclear reactions in the Russell diagram and the evolutionary tracks of the Sun and Capella.

THE EVOLUTION OF RED GIANTS

The reactions of the light elements that supply energy for the red giants differ from the solar reaction in one very essential regard. They do not possess the self-regenerative

"phœnix-like" property of the carbon-nitrogen cycle, and the nuclei entering these reactions never return to their original form. Thus, whereas the carbon and nitrogen nuclei act only as catalysers for the transformation of hydrogen into helium, the nuclei of deuterium, lithium, beryllium, and boron disappear rapidly in the process of energy production. Consequently, the time spent by a star in each stage of its evolution as a red giant must be considerably shorter than the period it will spend in the main sequence,* and all the successive stages of this "stellar infancy" represent only a small fraction of the total evolutionary life of each star.

We can now form a general picture of the early phases of stellar evolution, which will also describe, as one particular case, the past development of our Sun. According to this picture, each star begins its life as a giant globe of rather rarefied and cold gas containing a mixture of all possible chemical elements. The gravitational attraction among the different parts of the sphere causes its progressive contraction and hence a gradual rise in the temperature at its centre. As soon as the central temperature approaches the value of about one million degrees, the first nuclear reaction—the reaction between deuterium and hydrogen—begins in the stellar interior. The subatomic energy produced by this reaction stops any further contraction of the body of the star, and it remains in a more or less stable state as long as there is enough deuterium to keep the reaction going.

But as soon as the amount of deuterium becomes too small to provide sufficient energy for radiation, the con-

* Because the main-sequence state lasts as long as there is any hydrogen left, and hydrogen constitutes a very large part (35 percent) of stellar material.

traction process sets in again. After this, the star goes on contracting until the central temperature rises high enough to start the thermonuclear reaction between hydrogen and lithium; this halts the contracting process a second time.

Thus, shifting from one reaction to the next, and gradually increasing its central temperature and total luminosity all the while, the red giant finally approaches the region of the main sequence, where the catalysing action of carbon and nitrogen nuclei sets in. As the original proportion of light elements in the stellar body is probably no more than a fraction of one percent, their complete "burning" during the red-giant stage will result in only a small decrease of the total hydrogen content. But, as soon as the star enters into the main sequence, and its central temperature becomes sufficiently high to permit the carbon-nitrogen cycle to operate, the consumption of hydrogen will go on without interruption until it is used up to the last atom. And at this point begins the final contraction leading to the death of the star.

The evolutionary tracks corresponding to these three main successive stages of stellar development have been calculated by the author for two stars and are shown in Figure 40. The upper track is that of Capella A, which at present is still in the red-giant state. We see that this star is bound to enter into the main sequence when its luminosity has become several times higher than it is at present, and that it will later become one of the most luminous stars in the sky. The lower track belongs to our Sun, and shows that in its past history it must have been a giant red ball considerably less luminous than it is now. Stars still smaller than the Sun in their early stages possess such low

luminosities and surface temperatures that they are practically invisible.

PULSATING STARS

Early observations discovered the existence of stars whose luminosity did not remain constant, but fluctuated over regular periods of time. In many cases this variability was explained by the fact that the stars concerned were actually binary systems with the two components moving approximately in a plane parallel to our direction of vision. It is evident that in such cases one of the rotating components will from time to time come in front of the other, and that the repeated partial eclipse of the hind-star will cause a periodic decrease of light intensity.

In the upper half of Figure 41 we give a schematic representation of such an *eclipsing variable,* and also a curve representing the changes of the observed intensity which result from the overlapping of the two disks. The time-luminosity curve has a very characteristic shape, and shows a constant illumination periodically interrupted by more or less sharp minima.

But a careful survey of the skies has also shown the existence of other variable stars, which cannot possibly be explained by such a simple hypothesis. These stars, generally known as *cepheid variables* (after δ Cephei, the first star of this type discovered), exhibit very smooth and regular changes of luminosity, which can be very closely represented by an ordinary sinusoid curve (the lower half of Figure 41). The harmonic pendulum-like character of these observed luminosity oscillations suggests that they are due to *regular pulsations* of the whole stellar body between certain maximum and minimum values of the

diameter. Observations of the Doppler effect* in the spectral lines of cepheid variables actually prove that these

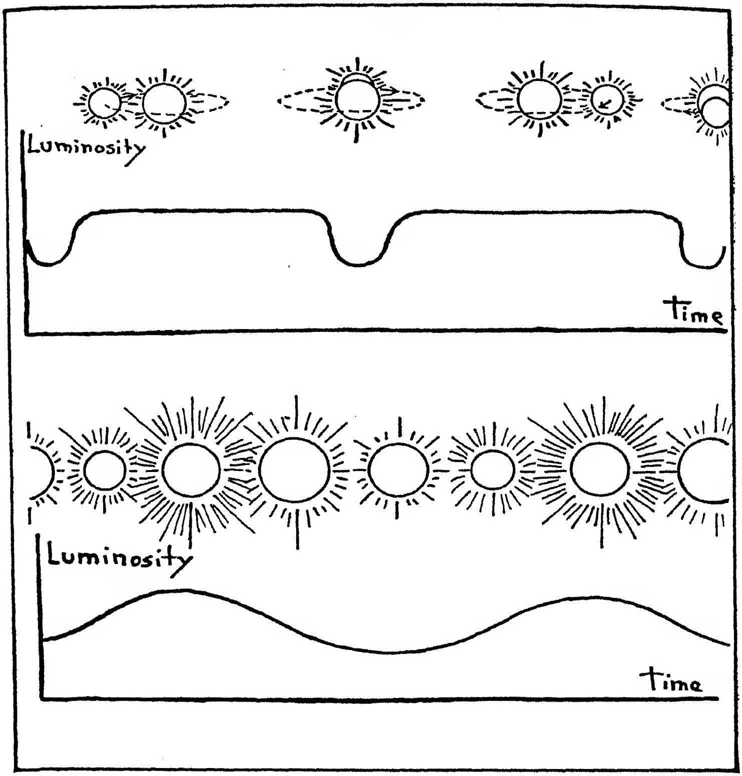


FIGURE 41
Eclipsing and pulsating variables with their corresponding luminosity curves.

* The so-called *Doppler effect*, previously referred to, consists of a change in the colour of the light emitted by a source moving relative to the observer. All the lines in the spectrum of a receding light source will be shifted toward the red end, whereas a source approaching the observer will show a shift toward violet. Thus, by comparing the spectrum of a stellar surface with the spectra of terrestrial light sources, we can detect periodic shifts of the spectral lines of the former if this surface is periodically moving to and fro.

stars are, so to speak, "breathing," that is, their surface layers are periodically rising and falling back again.

It is very important to note that, whereas the components of the eclipsing-variable systems are most often normal stars of the main sequence, *the phenomenon of pulsation has been observed exclusively among the red giants.* The pulsating stars form a sharply defined group, being situated on the Russell diagram within a rather narrow band (see Figure 37) at *the upper limit* of the region generally occupied by these dilute, cool stars.

THE THEORY OF STELLAR PULSATION

The mathematical theory of pulsating gas-spheres was first developed by Eddington, and it demonstrates a very interesting interdependence between the pulsation periods of the cepheid variables on the one hand and their geometrical dimensions and masses on the other. The laws governing stellar pulsations are quite analogous to those describing the harmonic vibrations of ordinary piano or violin strings. In the latter case the pitch (oscillation frequency) depends essentially upon the length and also upon the mass (thickness) of the vibrating string. A long string will give a lower note than a short one, and, with two strings of equal length, the lower note will come from the heavier (thicker) one. The pulsation period of gaseous stars increases with their dimensions and mass in exactly the same way.

It follows from Eddington's theory that the period is exactly inversely proportional to the square root of the average density, so that more dilute stars must pulsate more slowly than dense ones. Since, in the family of red giants, we have observed that the average densities drop with the

increasing masses and luminosities, we must conclude that *the heavier and brighter stars must possess longer pulsation periods.* This relation, which was first established by the Harvard astronomer H. Shapley on the basis of observational data, plays a very important role in stellar astronomy. In Figure 37 are shown the pulsation periods corresponding to various parts of the red giant region in the Russell diagram; they vary from values as short as several hours up to periods of several years.

THREE GROUPS OF PULSATING STARS

A detailed study of a large number of pulsating variables revealed that not all values for the periods are equally abundant, and that these stars can be subdivided by the length of their periods into three major groups. The first group contains the so-called *short-period, or cluster, variables* with periods lying between six hours and one day. Very few stars are known to possess periods of between one day and one week, but there are a good many that require from one to three weeks for one complete pulsation. This second class includes the famous δ Cephei itself, and the stars belonging to it are generally known as *normal cepheids.* Lastly, we find a large number of pulsating stars with periods crowded around the value of one year. These *long-period variables* are *mira variables,* so called after Mira Ceti (the "Wonderful" from the constellation of the Whale), which is the type representative of the class.

In Figure 37 the position on the Russell diagram of these three groups of stars is indicated by heavier shading. The explanation of this grouping of pulsating stars into three separate regions of the diagram is based on the theory

of energy liberation in the red giants discussed earlier in this chapter. We saw then that there are three distinct types of nuclear reaction responsible for the energy supply of these stars, and it is only natural to suppose that *the three groups of pulsating stars correspond to these three different modes of energy generation.*

If we compare the regions occupied by the three pulsation groups, as shown in Figure 37, with Figure 40, which represents the position of stars living on different nuclear reactions, we see at once that this suggested relationship must be quite correct. We find, in fact, that the long-period variables are the stars that receive their energy from the deuteron-proton reaction; that the cepheid variables are "burning" lithium, beryllium, and heavy boron; and that the short-period variables live exclusively on the lighter isotope of boron.

Thus, the observed pulsations of giant stellar bodies can be brought into a direct and simple connexion with the sequence of chemical elements in the periodic system.

THE CAUSE OF PULSATION

Why do stars pulsate, and, in particular, why is this property of pulsation found only in a certain narrow region of the Russell diagram? There are, of course, many causes which could bring the gaseous star out of a state of equilibrium. The close passage of two stars near each other, or a casual minute explosion in the interior, could easily do it. But in that case we should expect the pulsation to be an occasional phenomenon that would, moreover, not be strictly limited to one particular class of stars in the diagram. The narrowness of the region containing the pul-

sating variables indicates that we are dealing here with certain peculiar conditions that could be attained only once during the whole evolutionary life of a star.

The exact character of the conditions that could lead to the instability of these giant stellar bodies is not quite clear as yet, but the hypothesis recently advanced by the author strongly suggests that *the pulsations come as the result of a conflict between the nuclear and the gravitational energy-producing forces in the stellar interior.* It can, as a matter of fact, be shown that the region of the Russell diagram occupied by pulsating stars is characterized by the circumstance that the amount of energy liberated by thermonuclear reactions and the amount liberated by the gravitational contraction of the stellar body are of about the same order of magnitude. We might say that in these cases the stars "do not know which kind of energy production it is better to choose," and are "oscillating between the two possibilities." But this attractive hypothesis needs additional confirmation, and cannot be considered as definitive before some rather long and tedious calculations have been performed.

CHAPTER VIII

White Dwarfs and the Dying Sun

THE END OF STELLAR EVOLUTION

IN PREVIOUS chapters we have seen that, in the very distant future, when all the available sources of subatomic energy will finally have been exhausted, our Sun will begin its ultimate contraction. The gravitational energy liberated in this process will still keep the Sun hot and luminous for a while, but, as the process of contraction approaches its final term, the intensity of solar radiation will gradually begin to decline. And, after another long period, our Sun will turn into a giant lump of lifeless matter covered with eternal ice and surrounded by a system of frozen but still faithful planets.

When we speak of this "dead Sun" we are tempted, by analogy, to imagine it as a giant spherical stone, similar to our own planet but correspondingly larger in dimensions. We tend to imagine also that it will consist of various granites and basalts known to geology and that its interior will remain in a state of hot molten lava for a considerable time after the solid crust has been formed. But precisely because the Sun is so much larger than the earth, the analogy turns out to be quite wrong; for our present knowledge of the properties of matter indicates that the interior of the dead Sun will be in a rather different physical state from the interior of our earth or of any other of the planets.

THE COLLAPSE OF MATTER

In order to understand the physical causes that will prevent the formation of such a "granite Sun," let us imagine a mad architect who builds a house without limiting himself to a definite number of stories. As the house grows, he sends up more and more building materials, and every day more new floors are piled on top of the old ones. It will be clear, even to persons not familiar with the principles of civil engineering, that such a method will sooner or later lead to catastrophe. The lower walls of the house will give way under the increasing weight of the upper stories, and the whole house will collapse, turning into a formless heap of stones, considerably lower than the first stages of the construction. If our architect does not take into account the existence of a certain resistance limit of the building materials, the house will collapse as soon as the pressure at its base surpasses this limiting value.

Very similar difficulties arise in the case of too massive stellar bodies built from solid matter. The weight of the external layers of such bodies creates tremendous pressures in their central regions, and we must consider the possibility that the resistance of matter can be broken down if this pressure surpasses certain values. This puts limits to the possible geometrical dimensions of cold stellar bodies, beyond which, in the case of very large masses, there would be a complete collapse similar to the one in the example on page 161 (Figure 42).

"But the two cases are not quite analogous," the reader may say. "In the case of the house, the walls, which are subject to very strong pressure from above, will crack and spread sidewise. In the case of a giant spherical body, however, the material in the central regions is subject to a

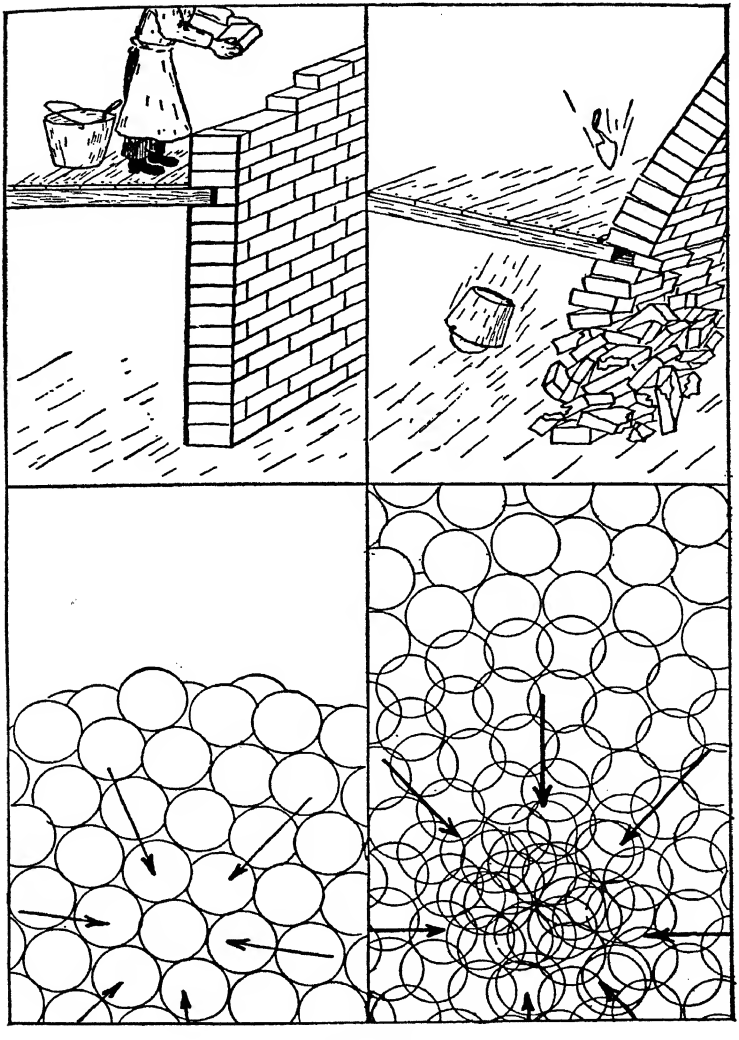


FIGURE 42
The collapse of a brick wall and of atoms, under the action of very large pressures.

uniform pressure *from all sides,* and there is, seemingly, no direction in which it could give way."

This is quite true, but, nevertheless, there is one direction of possible collapse that has been overlooked by this reader. We must not forget that matter is built up of a large number of separate atoms, and that the solid state is the state in which those atoms are most closely packed together. But we also know that atoms are not at all the absolutely rigid spheres that Democritus imagined them to be, but are in fact systems of electronic shells surrounding central nuclei. Now, under normal pressures, the forces obtaining between the structural parts of the atom stubbornly resist any attempt to squeeze it into a neighbouring atom; thus an increase of pressure will cause practically no change in the density of a solid body. But any resistance must have its limit, and, if the pressure surpasses a certain value, which is slightly different for different kinds of atoms, the electronic shells will be disrupted and the *atoms will be crushed,* like eggs packed in the bottom of a heavily laden basket.

Electrons belonging to one atom will then penetrate into the interior of another, and there will no longer be any sense in speaking of the electronic systems of individual atoms. Instead of an orderly system of electronic shells surrounding separate nuclei, our "atom crush" will present a picturesque mixture of bare nuclei and freely moving, unattached electrons, all rushing in disorder through space (Figure 43).

The rigidity of the solid state, caused by the mutual impenetrability of the electronic shells of separate atoms, will be gone, and an increase of outside pressure will lead to a corresponding increase of density. *Thus, at sufficiently*

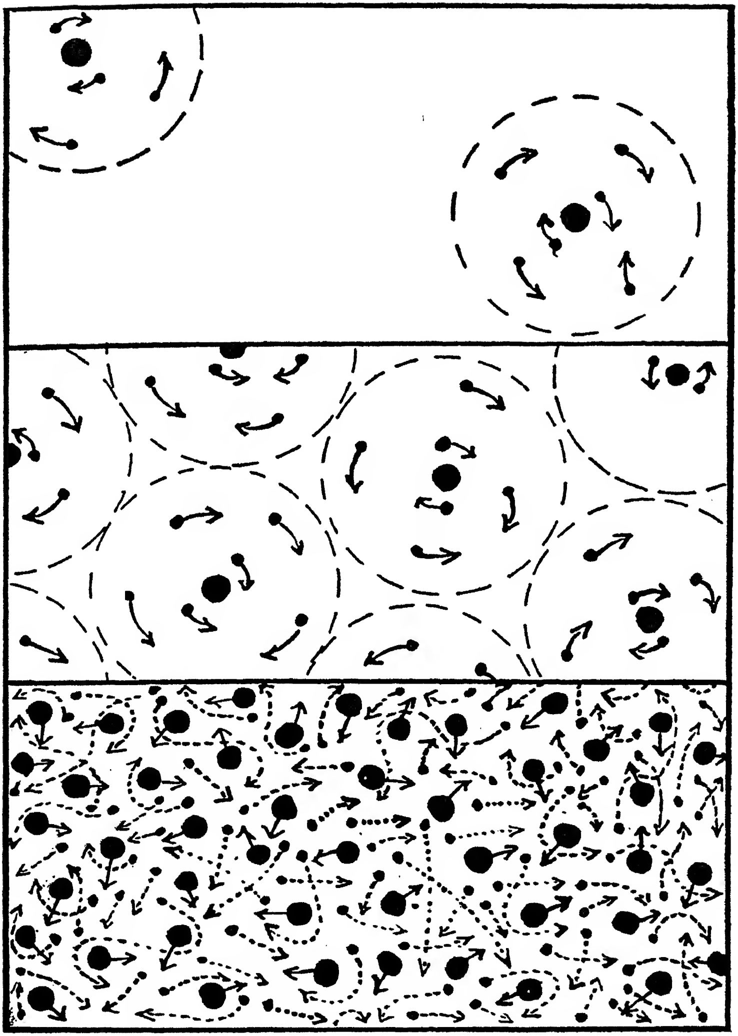


FIGURE 43
Gaseous, solid (or liquid), and crushed states of matter.

high pressures the solid (and liquid) state of matter, in the ordinary sense of these words, ceases to exist, and matter regains its compressibility.

THE PROPERTIES OF THE CRUSHED STATE OF MATTER

The state of matter that exhibits high compressibility under the action of outside pressure and a tendency toward unlimited expansion in the absence of it is usually designated in physics as the gaseous state, and *we are thus bound to consider the crushed matter described above as some kind of gas.* Of course, this gas will not at all resemble the ordinary gases to which we are accustomed in classical physics, and apart from its high compressibility it must look rather like some molten heavy metal. From the point of view of internal constitution this peculiar new state of matter will differ still more from ordinary gases in that it represents not a collection of separate atoms or molecules, but an irregular mixture of rapidly moving atomic fragments.

It should also be noted that, just as the *rigidity* of ordinary solid bodies is secured by the motion of atomic electrons along their quantum-orbits, so, too, the *elastic* properties of crushed matter are essentially dependent upon the electronic, and not the nuclear, part of the mixture. When diverted from their stable trajectories inside the separate atoms (by lack of space to move in), these torn-off electrons retain their *zero-point energy of motion* (see p. 166), which is mainly responsible for the pressure of the new type of gas. Thus, the same zero-point motion that prevents the electron from falling on its atomic nucleus, thereby securing the very existence of the atom, will also

secure the high gas pressure of the crushed state of matter, even at the lowest possible temperature.

The properties of this *electronic gas* were first investigated by the Italian physicist Enrico Fermi, and it is often referred to as *Fermi gas*. In particular, it was shown by Fermi that *the pressure of an electronic gas, and consequently the pressure of crushed matter, increases rather rapidly with its density, being inversely proportional to the* $\frac{5}{3}$ *power of the volume occupied.*

HOW LARGE CAN THE LARGEST STONE BE?

The discussion above will have made it clear why cold bodies massive enough to produce in their central regions pressures surpassing a certain *critical atom-crushing value* can no longer be considered to be giant stones; for the matter in their interiors completely loses the properties of a solid, and behaves in a way very similar to that of an ordinary gas. In order, then, for us to answer questions concerning the geometrical dimensions of such a collapsed stellar body, we must discuss in more detail the equilibrium conditions obtaining between the pressure of the Fermi gas of electrons, which fills its interior, and the forces of gravitational attraction among its various parts tending to compress it to still smaller radii.

Consider a giant sphere of crushed matter with a given mass and radius in which the state of equilibrium between gas pressure and the forces of gravity has been already reached. What would happen if, without changing the radius of this sphere, we were to double its mass? The total gravitational force tending to compress the sphere is composed of the attractive forces acting between the different parts of the body, as, for example, between the two volume

elements A and B, as indicated in Figure 44. By doubling the total mass of the sphere we double the mass contained in each of its volume elements. According to Newton's law, the forces of gravity are proportional to the *product* of the interacting masses. Thus, this doubling of mass will result

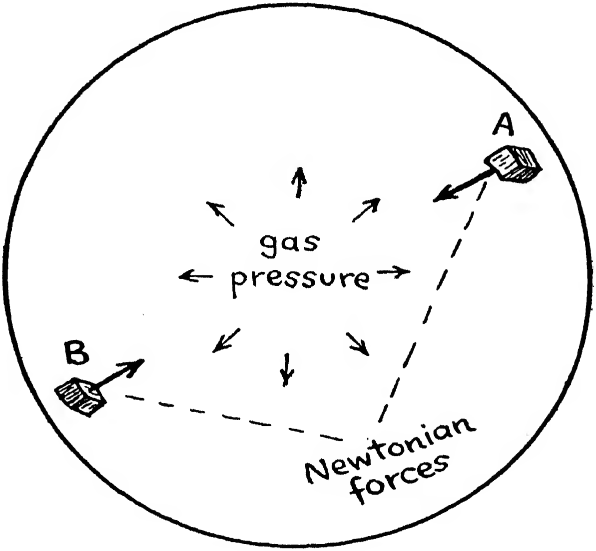


FIGURE 44
Equilibrium between gas pressure and the gravitational forces in a large sphere of gas.

in a fourfold increase of the total force tending to compress the sphere. On the other hand, according to Fermi's law (see p. 165), the pressure of the electronic gas filling the interior of the sphere will increase only by a factor smaller than four ($2^{\frac{5}{3}} = 3.17$). As a result, the balance will be destroyed in favour of the gravitational forces, and the sphere will begin to contract until equilibrium has been reached again for some smaller value of the radius.

We see from this that crushed matter is not a very suitable material from which to construct geometrically large bodies, and that the more material we put in, the smaller will be the final dimensions. *Thus, the finite resistance of atoms to high pressures puts a definite limit on the possible size of giant stones; bodies with a mass surpassing a definite upper limit cannot in principle be considered as solid bodies, and their geometrical dimensions will decrease with their increasing mass.*

JUPITER AS THE LARGEST STONE

To find the largest mass at which a body can still be considered a solid, in the ordinary sense of the word, we must first of all estimate the numerical value of the pressure necessary to crush atoms. This can easily be done on the basis of the present theory of atomic structure; and, according to the calculations of the Indian astrophysicist D. S. Kothari, this critical atom-crushing pressure amounts to 150 million atmospheres.

If we compare this figure with the value of 22 million atmospheres, which represents the pressure in the central regions of the earth, we must conclude, with some pinprick to our earthly pride, that our whole globe is not heavy enough to crush atoms by its weight. Only for Jupiter, the largest planet of our system (317 times heavier than the earth), does the internal pressure approach the critical values necessary for the collapse of matter; and we may expect that the atoms in the central regions of this giant body, if not yet crushed, are at least on the very verge of giving way under the tremendous weight of the outside layers.

All solid bodies more massive than Jupiter are inevitably

destined to a complete internal collapse, and their ultimate radii must be expected to become smaller than that of Jupiter. *Thus, Jupiter represents geometrically the largest piece of cooled matter that can in principle exist in the universe;* and the "dead Sun," in spite of its larger mass (or, actually, precisely because of it), will have a diameter considerably smaller than that of Jupiter, one comparable with the diameter of the earth (see Figure 45).

THE MASS-RADIUS RELATIONSHIP OF COLLAPSED BODIES

To find the exact values for the radii of collapsed stars in their dependence upon their mass, rather complicated mathematical calculations are, of course, necessary. Such calculations must naturally take into account not only the mass, but also the chemical constitution of the body in question. For, as we have seen above, the gas pressure of the crushed state of matter is given essentially by the number of free electrons resulting from the breaking down of the atoms; and, on the other hand, the weight of the outside layers tending to compress the stellar body is determined by the masses of bare atomic nuclei formed in the same process. Thus, the balance between these two opposing forces will essentially depend on the mass to be carried by the pressure of each free electron, which will be different for different chemical elements.

For example, in the case of pure hydrogen, there will be one proton mass for each electron freed by the crushing of the atoms, whereas, in the case of helium, two electrons will have to carry a nucleus of mass 4, so that *the mass per electron will be twice as large for helium as in the case of hydrogen.* It is clear, therefore, that a collapsed star formed

of pure helium would have to contract to a somewhat smaller radius than would a hydrogen star in order to attain a state of equilibrium.

This large difference, of the factor of two, between crushed hydrogen and crushed helium is, however, about as large as can be found as we proceed farther along the periodic system of elements. For, in all the other elements of the periodic system, the ratio of atomic weight (mass) to atomic number (number of electrons) remains always the same as, or only slightly higher than, that of helium. (For example: for carbon $\frac{A}{Z} = \frac{12}{6} = 2$; for oxygen $\frac{A}{Z} = \frac{16}{8} = 2$; for iron $\frac{A}{Z} = \frac{56}{26} = 2.15$.) From this we may conclude that collapsed stellar bodies formed of any of these elements will have nearly the same radii as if they were formed of pure helium.

Since, from the discussion in previous chapters, we have seen that the collapsed state of a star must represent the final stage of its evolution, it follows that *the hydrogen content in its interior is vanishingly small,** which means,

* In this particular question concerning the hydrogen content of collapsed stars, the opinion of most astronomers would be rather opposed to the views expressed above by the author. The point is that spectral analysis indicates the presence of considerable amounts of hydrogen in the atmospheres of the so-called white-dwarf stars, which, as we shall see later, actually are collapsed, or collapsing, stellar bodies. On this observational fact the opinion is usually based that these stars must also contain a great deal of hydrogen in their interiors. However, besides the almost unsurpassable difficulties which one encounters when one asks oneself how a star containing enough hydrogen for the production of thermonuclear energy could start a contraction process, the hypothesis of a high hydrogen content in the present interiors of white dwarfs stands in direct contradiction to our physical knowledge concerning nuclear transformations. It is not difficult to calculate that, *if there were any appreciable hydrogen content in the central regions of white dwarfs, the process of deuteron-formation from two hydrogen atoms* (as discussed in Chapter V) *would lead to an energy liberation surpassing by millions of times the observed*

in turn, that we may ignore the question of the kind of atoms involved and that the radius of a collapsed star is completely defined as a function of its mass.

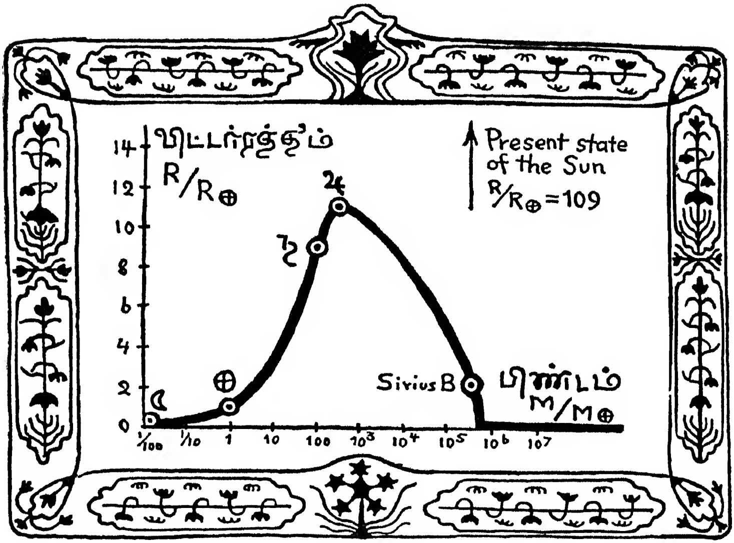


FIGURE 45

The relationship between the radii and the masses of cold stellar bodies, according to the calculations of the Indian astrophysicists Chandrasekhar and Kothari. The symbols ☾, ⊕, ♄, and ♃, respectively represent the moon, the earth, Saturn, and Jupiter. Note that for masses greater than 460,000 times the mass of the earth the radius becomes zero! The words for mass and radius are in Dr. Chandrasekhar's original Tamil.

In Figure 45 we give a graphic representation of the results of such calculations (in stars with a hydrogen content of zero) as carried out by another Indian astrophysicist

radiation of these stars. Thus, we should conclude that the presence of hydrogen in the atmospheres of the observed collapsed stellar bodies is only an occasional surface effect, and that it is just as dangerous to make conclusions about stellar interiors on the basis of atmospheric analysis as it would be to conclude from looking at the map of our globe that the body of the earth consists two-thirds of water.

S. Chandrasekhar, to whom we owe the most complete study of the collapsed states of stellar bodies. We see that for bodies less massive than Jupiter, the volumes increase in direct proportion to the mass, which, of course, should be expected for the ordinary uncollapsed state of solid bodies. But for larger masses the situation is essentially changed; and, owing to the collapse of matter in the interior, the volume of the body begins to decrease with the increasing mass. In particular we find from this curve that the radius of the "dead Sun" will be 10 times smaller than the radius of Jupiter, and comparable with the radius of the earth. *The average density of the Sun in this ultimate stage of its evolution will exceed the density of water by a factor of 3 millions.*

Because of the high compressibility of the crushed state of matter, the density of this highly compact body will not be uniform (as it is, for example, in our globe) and will rapidly increase toward the centre. According to the calculations of Chandrasekhar, the central density in this case must exceed the average density by a factor of 10, so that *each cubic centimetre of the material in the central regions of the dead Sun will weight about 30 tons.* Such will be the unusual conditions under the thick layer of eternal ice covering the surface of our Sun when it will finally have reached the end of its life.

WHITE DWARFS

"Well," the reader will probably now be saying, with a tone of scepticism, "this is, indeed, a very exciting picture, but who is to vouch for its correctness? Without Mr. H. G. Wells's time-machine it is not likely that anyone will actually live several billion years into the future and check this

prediction. But I should believe it better if I could see such a dead or dying Sun myself."

We can, of course, hardly show the reader the actual dying stages of our own Sun, nor can we hope to see stars that are quite dead, since these emit no light; but we need only look around among the stars surrounding us in order to find such as have already exhausted all their hydrogen content and are slowly approaching their deathbeds. Thus we shall find plenty of observational evidence for the existence of collapsed stellar bodies that have not yet quite reached their final state and are still living on the gravitational energy liberated by their slow contraction. Such stars should be distinguishable from all other "still living" stars by *their comparatively low luminosities and abnormally small radii corresponding to very high densities.*

The first and most typical example of this moribund stage in stars is the "companion of Sirius." We have already seen that Sirius is a normal star of the main sequence analogous in all its properties to our Sun. It is not Sirius, however, that interests us at present, but a star 13,000 times fainter, a mote in the dog's eye, revolving around Sirius and rather close to it. This faintness and proximity to Sirius prevented its discovery until comparatively recent times, by Clark in 1862. The first indication of its presence had been given in observations of the motion of Sirius, whose track among the fixed stars, instead of being a straight line, as one should expect of a single body freely moving in space, was found to be represented by a winding line, which suggested that some second body was disturbing its motion.

To the great surprise of astronomers, the light emitted by this newly discovered stellar companion of Sirius, instead of being rather reddish in colour, as would be suit-

able for such small luminosity, turned out to be brilliantly *white,* indicating a very high surface temperature of about 10,000 degrees. This character of the radiation, combined with its very low total luminosity, earned for the companion of Sirius, and for other later-discovered stars of the same type, the rather poetical name of *white dwarfs.*

It is easy to see that the observed properties of Sirius's companion fit very closely to the theoretical requirements we formulated above for dying stars. If a stellar body of such high surface temperature (and consequently of high energy-emission per unit surface) possesses an extremely small absolute luminosity, we must inevitably conclude that its geometrical dimensions are very small as compared with the dimensions of normal stars. From the total luminosity and the surface temperature of Sirius's companion, it can easily be estimated that its surface area is 2500 times, and its radius 50 times, smaller than those of our Sun.*

On the other hand its mass, estimated from its rotation period around Sirius, turns out to be almost equal to the mass of the Sun (95 percent), *thus bringing the average density of this star to the tremendously high value of 200,000 times the density of water.* We see, therefore, that, as was first indicated by R. H. Fowler, the white dwarfs really represent the collapsed states of stars, the possibility of which we predicted above on the basis of purely theoretical considerations.

* The most exact values of the radii of white dwarfs are given not by the study of their surface temperatures, but by measuring the so-called *red shift of spectral lines* predicted by Einstein's theory of relativity for high gravitational potentials. Owing to the large masses and small radii of white dwarfs, the red shifts in their spectra are comparatively large and can easily be measured and will serve for exact estimates of their radii if the mass is known. The values given in this book are based exclusively on such measurements.

If we plot the observed mass and radius of Sirius's companion on the theoretical curve for collapsed stellar bodies (Figure 45), we shall see that its present radius is still 2.5 times larger than it should be in its final state. This fact suggests that this particular white dwarf has not yet quite reached the final stage of its contraction, or that the present estimate of its radius is wrong by at least a factor of two.

WHEN OUR SUN IS DYING

There is hardly any doubt that, after several billions of years, our Sun, in its decline, will look rather as Sirius's companion looks at present. At that distant future date the visible angular diameter of the Sun, as seen from the surface of the earth, will be about the same as the present visible diameter of the planet Jupiter, so that an ignorant observer would classify the Sun as an extremely bright distant star.

In spite of this small angular diameter of the "Sun-star," its light will still be considerably more intense than that of any other star in the sky. The illumination of the surface of our planet in the middle of the day will be 1000 times brighter than that given by the full moon, but the moon itself will be so poorly illuminated by the dying Sun that it will be practically invisible. The temperature of the earth will drop down to 200 degrees below the freezing-point (— 328° F.), making any kind of life on the earth's surface quite impossible. But all these inconveniences of darkness and cold will probably be of no importance to humanity, which, as we have seen in Chapter V, will have been burned to death by the increasing solar activity long before the ultimate contraction and thermal death commences.

CHAPTER IX

Can Our Sun Explode?

THE NOVÆ

ALL the evolutionary changes in the history of stars discussed above are extremely slow from our human point of view and require at least several millions of years to become noticeable. Thus, even when applied to our own Sun—its progressive heating up, and its ultimate contraction to follow upon the state of maximum luminosity—they represent for earth-dwellers matters of purely theoretical interest only. But observation of the skies reveals the occurrence of much more catastrophic events, leading to a complete change in the status of a star within only a few days or even a few hours.

Quite unexpectedly, and without any preliminary indications, *a star will blast into an intensity surpassing that of its normal state by a factor of several hundreds of thousands and, in some cases, even of several billions.* The star, which before this explosion may have been very faint and inconspicuous, will suddenly become one of the brightest in the sky and attract the attention of astronomers and the superstitious. This state of maximum intensity will not, however, last long, and, after rapidly reaching its greatest brilliance, the exploded star will gradually begin to fade, returning to its original luminosity within a year or so.

Early pretelescopic observations of such stellar explosions had previously failed to notice the original states of

the stars involved (because in most cases they could not be seen by the naked eye), and the exploding stars therefore received the somewhat misleading name of *new stars* or *novæ*. Several recordings of the appearance of extremely bright novæ of this kind may be found in ancient history, and, in particular, it is very possible that the "Star of Bethlehem" represented one of these cosmic catastrophes.

In more recent times, a brilliant stellar explosion was observed in November 1572 by the famous Danish astronomer Tycho Brahe; during the period of its maximum luminosity this star could be seen even in daylight. Another luminous nova appeared soon after that, in 1604, and is usually connected with the name of Johann Kepler, who gave us the laws of planetary motion. After these two brilliant explosions, commemorating two brilliant names in the history of astronomy, the skies remained comparatively calm until the year 1918, when a star of very great luminosity, surpassing even that of Sirius, appeared for a while in the constellation Aquila and presented the first convenient case for study by modern observational methods (Plate VIIIA).

It must be clear, however, that, apart from these very conspicuous novæ, there must also be a large number of stellar explosions which, because of their vast distances from us, are too faint to be detected visually. Indeed, the modern systematic survey of the skies by means of photography indicates that at least twenty such explosions take place yearly among the stars forming our own stellar system.

TWO CLASSES OF STELLAR EXPLOSION

We have seen above that novæ differ very widely in their observed brightness, some being so luminous that they can

easily be seen in the daylight, whereas others are accessible only to telescopic observation. To a great extent these differences are due to the unequal distances separating us from the exploding stars, and, when corrected for the distance, most of these luminosities come much closer to each other and average about 200,000 times the normal luminosity of the Sun.

These do not include, however, such exceptional cases as the Bethlehem or Tycho stars, which must have been considerably more luminous. The study of all the available historical data on these exceptionally bright novæ brought the astronomer W. Baade and the physicist F. Zwicky to the very interesting conclusion that we are here dealing with *an essentially different class of stellar explosions,* a class that has received the name of *supernovæ.* The maximum luminosity of these supernovæ is, on the average, 10,000 times greater than that of ordinary novæ and *exceeds by a factor of several billions the luminosity of our Sun.* Most of the historic novæ probably fall into this class, and the Kepler star of 1604 was apparently the last explosion of this type within our stellar system.*

From the historical data, Baade and Zwicky also estimated that *the average frequency of appearance of supernovæ in our stellar system is about one in every three centuries.* During the 336 years separating us from this last "superexplosion," there has been no other similar catastrophe in our stellar system, and we may permit ourselves the fairly good hope that modern astronomy will soon have the pleasure of observing another phenomenon like that of the Bethlehem, Tycho, and Kepler stars.

* The Nova Aquilæ 1918 was a normal nova, and its high visual luminosity was due only to its comparatively short distance from us.

"What a bad joke on the astronomers," the reader will probably think, "that the supernovæ represent such rare phenomena, and that one must wait centuries to see one. It must take at least a couple of thousand years before sufficient observational evidence of these explosions has been accumulated!"

But the situation is not really so bad as all that. As we shall see in the following chapters, our stellar system, composed as it is of about 40 billions of individual stars, is not the only system of this kind in all the infinite universe. Very, very far away, at distances much greater than those separating us from the most remote stars of our own system, astronomical observations reveal the existence of other concentrations of stars floating freely in the vast spaces of the universe. These remote stellar systems can be seen from the earth only as very faint nebulosities of regular spherical or elliptical shape, and are known to astronomers as *extragalactic nebulæ.** Popular literature christened them with a more appropriate name, "island universes." Many thousands of these remote systems, similar to our own stellar system of the Milky Way, have already been catalogued, and the most powerful telescopes reveal still larger numbers of these "stellar islands" in the remotest corners of the universe.

Now, thought Dr. Zwicky, as he inspected the list of extragalactic nebulæ, if these numerous stellar accumulations are really analogous to our own system, they must

* The use of the term "nebulæ" for these celestial objects dates back to the time when they were believed to be similar to the real nebulæ, that is, the rarefied luminous gases in interstellar space of our own system (compare Plate XI). It is known now beyond any doubt that these extragalactic "nebulæ" actually are concentrations of billions of individual stars.

also show the supernova phenomenon. And if each nebula experiences a supernova explosion at the average rate of one every 300 years, I have a fairly good chance of finding one supernova before it is time for summer vacations.

Picking out from the catalogue several hundred conveniently situated extragalactic nebulæ, Dr. Zwicky began a systematic survey by photographing the selected regions of the celestial globe almost every night. For a couple of months no changes took place in any of the nebulæ under observation, until finally, during the night of February 16, 1937, there was a brilliant flash in one of them. It is not known—though he surely would have been justified—if Dr. Zwicky yodelled, after the fashion of his native country, when he saw his first supernova.

Yes, it was a supernova, a terrific explosion that took place in the nebula that is registered under the name N.G.C. 4157 and is separated from us by the tremendous distance of 40,000,000,000,000,000,000 kilometres. Strictly speaking, the actual explosion had taken place long before Zwicky began his investigation, and even before man appeared on the surface of the earth. To cover the distance between the nebula N.G.C. 4157 and the earth the light required 4 millions of years; and all this time since the explosion the light rays had been travelling through the vast empty spaces of the universe to enter Zwicky's telescope and make the photographic impression reproduced in his article in the *Publications of the Astronomical Society of the Pacific.*

Since this first success, about twenty fairly well-established cases of supernovæ have been detected in various, more or less remote, extragalactic nebulæ (see Plate VIIIB).

THE CHANCES OF OUR OWN SUN'S EXPLODING

Once we had observed a star, apparently quite peaceful and quite indistinguishable from billions of others, suddenly—within a few hours—burst into a terrific explosion, the doubt inevitably crept into our minds: will our Sun not play the same trick on us, today, tomorrow, or next year? If, one fatal day, our Sun should choose to become a nova, the earth (and all the other planets as well) would instantly be turned into a thin gas; and it all would take place so fast that nobody would even have time to realize what had happened. Only the astronomers, if there are any, on some distant planetary system of another star would register the appearance of a new nova and would probably begin the study of its spectrum. But before this unpleasant experience overtakes us, if it ever does, it may be interesting to speculate about the chances of its happening, to see whether there is any possibility of predicting in advance the date of the catastrophe.*

We must admit, to start with, that *the a priori chances of our Sun's becoming an ordinary nova once during its total life period are fairly high.* As a matter of fact, we have seen that at least twenty stars of our stellar system explode yearly. Since our universe is about 2 billion years old (see Chapter XII), it follows that some 40 billion stars have already exploded during this period (unless, which is rather improbable, there is a certain preference for such explosions in the present epoch). On the other hand, as we shall see from the following chapters, our stellar system contains only about 40 billion individual stars. Thus, we must

* Such a prediction would, of course, be of no practical use whatever unless a method were found to detach our earth from the solar system and send it travelling away long before the explosion.

conclude that practically every star must explode at least once during its evolutionary history. But the *a priori* chance of a solar explosion *within the next few years* is still only about one in several billions, so that such an explosion is much less probable than many other unpleasant events that can happen to humanity.

Also, probably each star can explode only once during its lifetime, and perhaps our Sun has already exploded in the very remote past? This question can hardly be answered before we know more clearly the nature of the physical processes leading to such catastrophes.

There is a Russian proverb: "If you must die, die with pomp," and we may wonder whether the explosion of our Sun will make, not an ordinary nova, but rather a supernova. This will not make any difference to us personally, but it will look so much nicer from the outside! It seems, however, that to ask for a superexplosion of our Sun is to ask too much. The supernova phenomena are very rare, and only certain selected stars have the privilege of showing such a splendid fireworks display. As we shall see later, these superexplosions probably take place only in the case of stars much larger and heavier than our Sun, so that we shall have to be satisfied to have our end announced through the universe only by a comparatively inconspicuous nova.

THE PRENOVA STAGE OF STARS

One of the most direct methods of discovering whether our Sun is at present in the *pre-explosive state* would be to compare its characteristics with those of stars that were later to become novæ. Such comparisons might even reveal certain specific features of stars preparing to burst,

and the absence of such features in the case of our Sun would guarantee its stability for a fairly long period of time.

Unfortunately, however, very little is known at present about these *prenova stages* of exploding stars. It is true that, in several instances of rather bright novæ, the study of the old photographs of the corresponding regions of the sky, taken before the explosion, always revealed the presence of a faint star at exactly the same spot where the nova was seen later. The estimates of distance permit us to conclude also that in some cases this prenova stage went with an absolute luminosity comparable with that of our Sun, whereas in other cases the absolute luminosities were either higher or lower. But, since no one knew in advance that these particular stars were going to explode, their spectra and other properties had not been investigated in detail.

Only in the case of Nova Hercules, which flashed on the northern sky in mid-December 1934, had the spectrum been photographed occasionally before the explosion. And the spectrogram reveals that before the explosion this star was not much different from any other star of the main sequence. In fact, its absolute luminosity and its spectral characteristics were very close to those of our Sun. Does this mean that our Sun is also destined to burst in a not very distant future? Not necessarily. First of all, a "not very distant future" might mean millions of years in the astronomical time scale, and, besides, there are millions of stars possessing the same characteristics which are not exploding.

The preparations for these explosions apparently do not much change the observable surface properties of stars; if there are some minute alterations, they have escaped obser-

vation. The example of Nova Hercules 1934 tells us only that the star need not necessarily possess some clearly abnormal external properties in order to be able to explode, and that an apparently perfectly normal star can burst into a terrific explosion if it chooses to do so.

It should be noted that the pre-explosive states of supernovæ are much more difficult to observe. In fact, except for a few historical outbursts, they all belong to very distant stellar systems, so far from us that no individual stars can be distinguished. Only supernovæ at their maximum can be clearly seen in these distant worlds, owing to the fact that *the radiation emitted by such explosions is comparable, and in some cases even surpasses, the total radiation of the billions of other stars forming those systems.**

THE PROCESS OF EXPLOSION

As was mentioned above, the main external feature of a nova outburst consists in the fact that the luminosity of the star increases tremendously within a short period of time, and then begins to drop back to its original value. In Figure 46 we give the luminosity curves for Nova Aquilæ 1918 already cited, and for the supernova that appeared in 1937 in the extragalactic nebula known as I.C. 4182 (the photographs of the development of the latter are given in Plate VIIIB). We see that, apart from the amplitude, the two curves show a very similar character, with a very rapid rise in the beginning and a slow and somewhat irregular decrease of radiation after the maximum.

* In fact, since supernovæ are billions of times more luminous than the average normal star, and since the average extragalactic nebula contains several billions of stars, the appearance of a supernova might double the total light emitted by such nebulæ.

Other important characteristics that change during the explosion are the surface temperature and the spectrum of the star. Whereas in the prenova stage all stars evidently

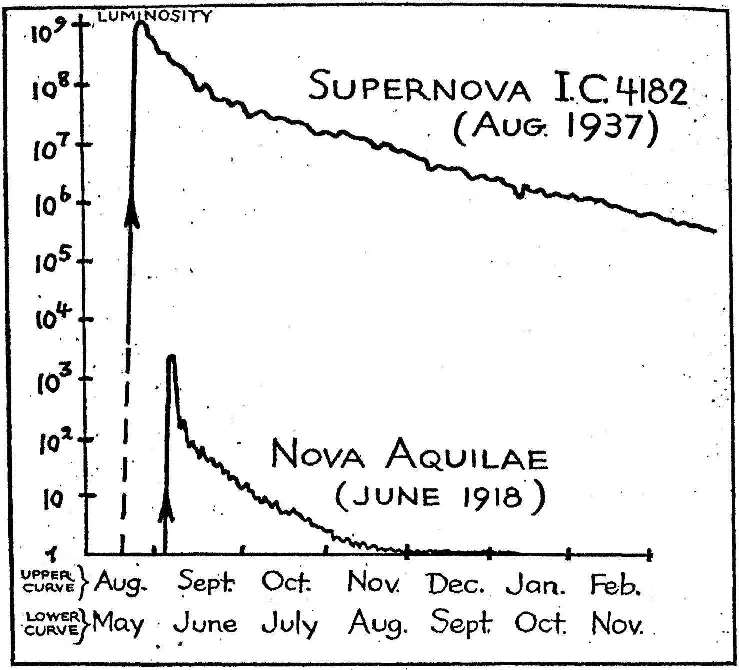


FIGURE 46
The luminosity changes of a typical nova and a typical supernova. Luminosities are given in terms of the luminosity of the Sun (=1).

possess a normal spectrum belonging to one of the Harvard classes, during the explosion the spectrum completely changes it character, indicating temperatures running into hundreds of thousands, if not millions, of degrees. But the study of these explosion spectra also reveals another extremely interesting effect. The bright emission lines of

PLATE IX. A "planetary" or "ring nebula" in the constellation Lyra. This is probably the result of a nova outburst of several centuries ago. (See p. 185.) (Mt. Wilson photograph.)

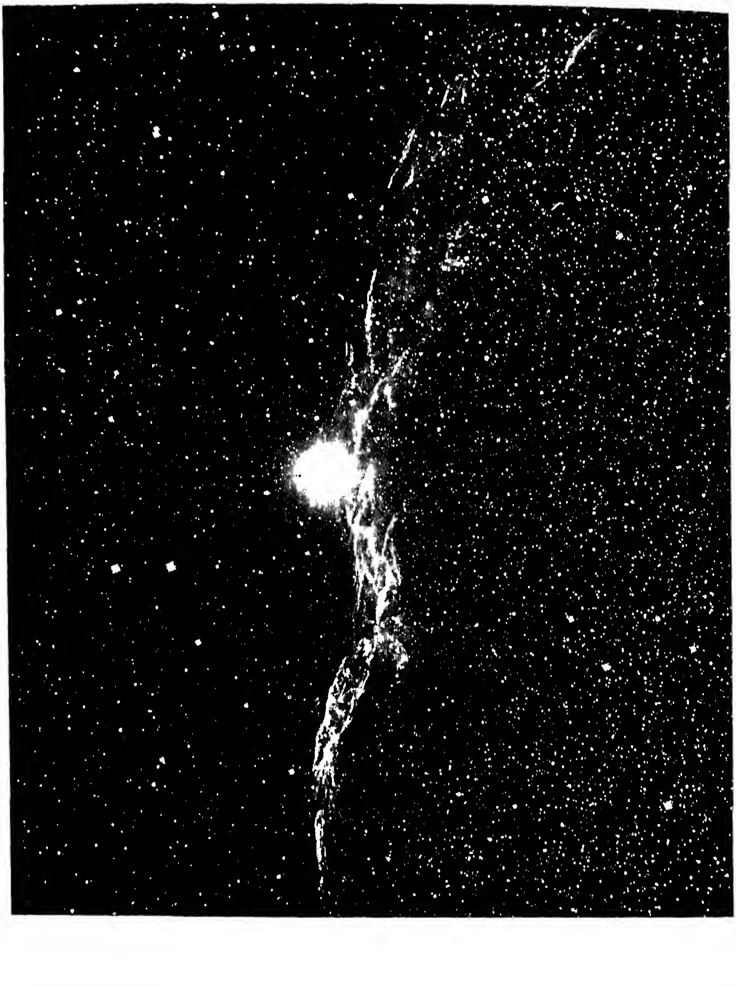


PLATE X. The filamentary nebula in the constellation Cygnus. This is probably the remainder of a gaseous shell ejected by a supernova about 100,000 years ago. The bright star in the centre is not a part of the nebula, but appears there only by coincidence. (See p. 186.) (Mt. Wilson photograph.)

novæ show a conspicuous shift toward the violet end of the spectrum, indicating a rapid expansion of the gaseous shell that is formed around the star during the process of explosion.

In the best-studied case, Nova Aquilæ 1918, the expansion velocity of this shell was estimated to be about 2000 kilometres per second, and six months after the explosion it became directly observable through the telescope. The diameter of this faint greenish nebulosity enveloping the star is now gradually increasing at the rate of two angular seconds per year; and, if the velocity remains constant and the shell does not fade in the course of time, it will attain the visible diameter of the moon about a thousand years from now.

Incidentally, astronomical observation has revealed the existence of a considerable number of bright hot stars that are surrounded by rather extensive gaseous envelopes. The question whether these so-called *planetary nebulæ* (again a quite unsuitable name!) actually represent the later stages of nova development is as yet unanswered (see Plate IX).

We cannot pass on from here without mentioning also the case of the irregular gaseous nebula* in the constellation Taurus, known as the "Crab Nebula" because of its peculiar shape. This nebula is at present rapidly expanding at the rate of 0.18 angular second per year, from which we conclude that the expansion must have started about eight or nine hundred years ago. Was the mass of gas that forms the Crab Nebula exploded from some nova, or

* We remind the reader once more that the giant "extragalactic nebulæ" made up of stars, and the much smaller "gaseous nebulæ" to be found in our own stellar system, are absolutely different things in spite of their similar names.

rather, judging from the intensity of the effect, from some supernova, which flashed on our sky at that epoch? The study of Chinese manuscripts of the eleventh century reveals that there actually was at that time a very brilliant stellar explosion, which took place in A.D. 1054 almost exactly in the same place where we now see this curious nebula. Thus, there is scarcely any doubt that the Crab Nebula is the result of a supernova explosion that was observed 886 years ago.

Another interesting example is furnished by the so-called "Filamentary Nebula" in the constellation Cygnus (Plate X). This is shaped like the arc of a circle, and, together with some other nebulæ of similar type, forms a rather regular loop, with an angular diameter of about 2 degrees (four moon diameters). The nebulæ forming this loop move from their common centre with an angular velocity of 0.05 second per year, so that the expansion must have begun about 100,000 years ago. Most probably this is also the result of a supernova explosion, but unfortunately in the year 100,000 B.C. there were no astronomers, even Chinese ones, to record the appearance of the new star.

The recent observations of G. P. Kuiper at the Yerkes Observatory have shown that this "blowing of smoke rings" is not the only consequence of stellar explosions. When Nova Hercules 1934 was telescopically examined a few years after its appearance, it became obvious that the star had probably been broken into two parts by the force of the explosion. The two fragments are now travelling away from each other with a relative velocity of about 0.25 angular second a year, and will be separated by a visual distance equal to the visible diameter of the moon (0.5 degree) by the year A.D. 9130. In Figure 47 we give the

observed relative distances of the two fragments of this stellar explosion.

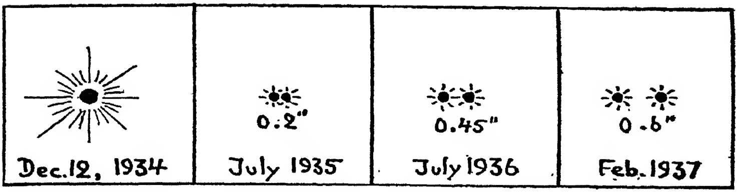


FIGURE 47
The increasing separation of the two fragments formed by the explosion of Nova Hercules on December 12, 1934.

WHAT CAUSES STELLAR EXPLOSIONS?

What are the physical processes that cause the explosion of seemingly normal stars? We must confess that we do not know at present, and can only speculate about the different conditions that might possibly be responsible for these catastrophic events.

The oldest, and probably the simplest, hypothesis is to the effect that the observed explosions are due to *external causes*, as, for example, a collision with some obstacle the star meets on its way through space. It is known, however, that, owing to the extremely sparse population of space, the chances of collisions between stars are negligibly small. In fact, it has been calculated that not more than two or three such collisions could have taken place in our stellar system in the past 2 billions of years.

But we know that interstellar space contains very extensive rarefied gaseous material, evidently left over after the formation of the individual stars. These interstellar clouds, known as *gaseous nebulæ,* are often illuminated by the light of neighbouring stars, and appear as giant luminous nebulosities of very irregular and picturesque shape (see

Plate XI). In other cases they are dark (see Plate XII), and can be observed only through their obscuration effect on the stars situated behind them. The two well-known dark holes in the Milky Way, named the "Coal Sacks" by astronomically inclined seamen, represent typical examples of such dark nebulosities.

If a star, moving through space at a very great velocity, enters such a cloud of dilute material, it will burst into high luminosity in the very same way as does a meteorite that enters our terrestrial atmosphere. And, in fact, the kinetic energy of stellar motion, when thus transformed into heat, can easily supply the tremendous radiation characteristic of novæ during the period of their high luminosity. If, for example, the motion of our Sun (whose present speed is 19 kilometres per second) were slowed down to half its present value by the friction of such a gas cloud, the liberated kinetic energy would suffice for a millionfold increase of its luminosity over a period of several weeks.

This hypothesis, however, simple though it is, meets with serious difficulties in the attempt to explain the remarkable similarity of all observed nova explosions. For, since the gaseous nebulæ that different stars might meet vary so widely in their densities and geometrical dimensions, it is hard to see how they could have such strikingly similar effects. It must also be noted that this purely *kinetic hypothesis,* though it accounts for enough energy to create ordinary novæ, is absolutely inapplicable to supernovæ, with their considerably larger energy liberation.

If we try to solve the problem of stellar explosions in terms of nuclear transformations, which are so important in the normal life of the star, we must think of some

PLATE XI. The luminous gaseous nebula in Orion. This giant mass of gas is inside our Galaxy and probably owes its luminosity to the radiation of the surrounding stars. (See p. 188.) (Mt. Wilson photograph.)

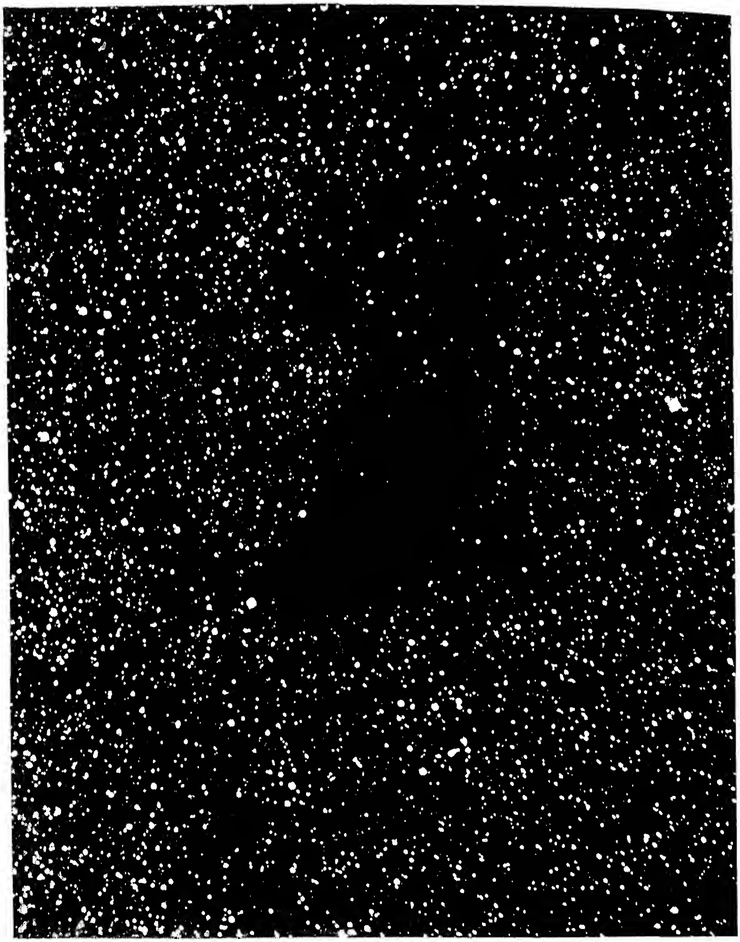


PLATE XII. A portion of the Milky Way near the constellation Aquila, showing its resolution into a large number of individual stars. The dark spot in the centre is not a "channel" but a dark gaseous nebula obscuring the view. (See p. 206.) (Mt. Wilson photograph.)

special thermonuclear reaction that will suddenly come into play when the central temperature of the evolving star reaches a certain critical value. A very small amount of such an "explosive element" might indeed be enough to liberate the energy required for an ordinary nova and even for a supernova, but no possible reaction of this kind has as yet been found.

So we must confess that we do not know why stars explode, and that we cannot tell for certain whether our Sun is going to follow the example of Nova Hercules in the near or distant future. Let us hope it will not.

SUPERNOVÆ AND THE "NUCLEAR STATE" OF MATTER

In the particular case of supernovæ, an entirely novel mechanism of explosion was proposed as a possibility by Zwicky, soon after he had proved the occurrence of these vast stellar catastrophes. In order to understand Zwicky's hypothesis, we must go back to our discussion of superdense stars in Chapter VIII. We saw there that, after the consumption of all the hydrogen available for thermonuclear reactions, every massive star is bound to contract to a very small radius and a correspondingly very high density.

In Figure 45 of that chapter we also gave a graphic representation of the fact that the radius of a collapsed star is a function of its mass, demonstrating that this finite radius decreases with the increasing mass. When he saw this diagram, the careful reader may already have noticed that the curve expressing this radius-mass relationship does not extend indefinitely in the direction of larger masses, but leads to a zero radius for a mass that is equal to 1.4

Sun masses. This means that *the minimum radius for all contracting stars heavier than 1.4 Suns is zero,* or, in other words, that *all sufficiently heavy stars are bound to have an unlimited contraction.* The weight of the outside layers of these heavy stars is so great that the pressure of Fermi's electronic gas in the interior is never able to balance it, and no stable equilibrium with a finite value of the radius is possible.*

What will happen to a very heavy star that is contracting, mathematically speaking, to a geometrical point? The answer to this question was first given by the young Russian physicist L. D. Landau, who pointed out that the contraction must stop as soon as the distances between the separated electrons and atomic nuclei that make up stellar matter become equal to their diameters. At this stage of compression, the nuclei and electrons, being brought into direct contact, will stick together, as would separate drops of mercury so brought together, and will form in the stellar interior *a continuous "nuclear substance"* (see Figure 48).

The hypothetical high "rigidity" of this form of matter must finally stop the progressive contraction of heavy stars, and in the resulting state of equilibrium *the stellar interior will be occupied by a giant nucleus, quite analogous to ordinary atomic nuclei, but measuring many hundreds of kilometres in diameter.* Being made up of atomic nuclei and electrons that have been torn apart by the crushing of originally neutral atoms, this *stellar nucleus will be, on*

* The reader must not forget, of course, that all this pertains only to stars deprived of hydrogen and living on the gravitational energy liberated in contraction. In all young stars containing hydrogen, thermonuclear reactions produce sufficient energy to keep up a central temperature and gas pressure high enough to maintain stability.

*the whole, neutral and will possess a density surpassing the density of water by a factor of several thousand billions.**

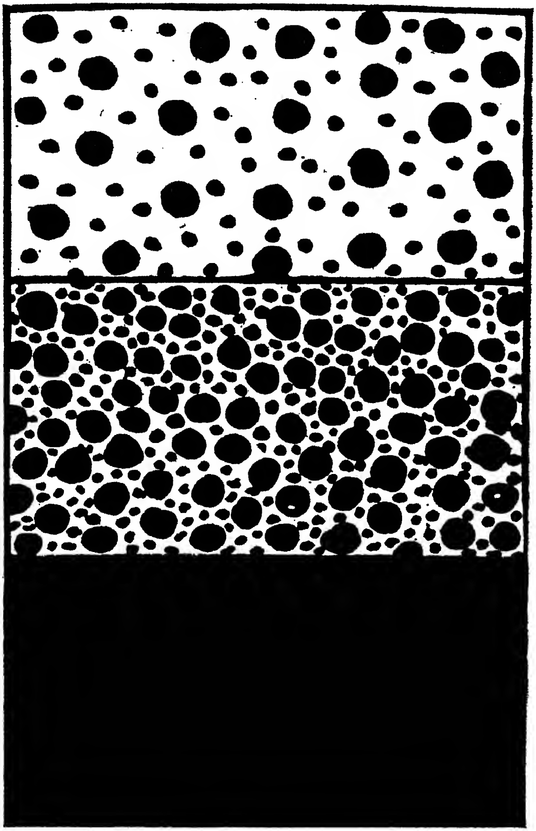


FIGURE 48
Formation of the "nuclear state" of matter by very high pressure (compare Figure 43).

* In water the atomic nuclei are on the average 10^{-8} centimetre apart, whereas in the nuclear substance these distances are reduced to nuclear diameters, or 10^{-12} centimetre. This linear compression by a factor of 10,000 will give an increase of density by a factor of 10^{12}, i.e., 1,000,000,000,000.

A small dust particle made from such dense matter would weigh several tons! But, it must be clear, of course, that matter in this "nuclear state" can exist only under the tremendous pressures existing in the interior of heavy contracting stars. When brought out from these regions, it will immediately expand, splitting into separate nuclei and electrons, and forming the atoms of different stable chemical elements.

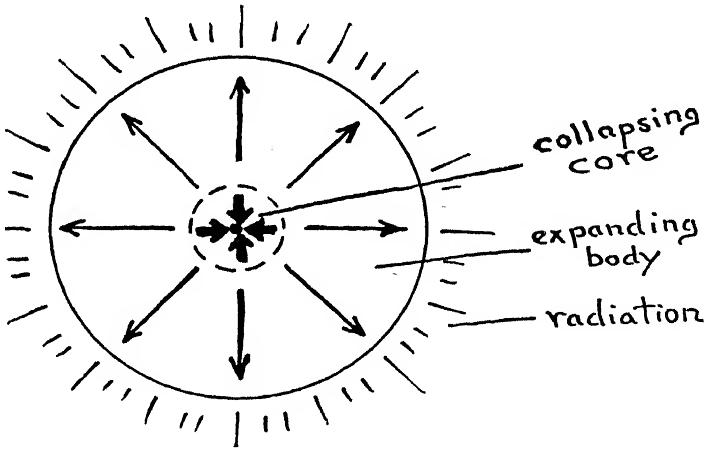


FIGURE 49
The hypothetical collapse of the central regions in a supernova.

Let us now return to Dr. Zwicky's hypothesis concerning the catastrophic events observed in the supernovæ: it is to the effect that what we witness here is the tremendously rapid collapse of heavy stars resulting from the formation of such "nuclear states" of matter in their interiors. The process probably begins with the neutralization of bare atomic nuclei in the stellar interior through their absorption of free electrons that are squeezed too close to them

by outside pressure. This is then followed by the sticking together of the neutral particles thus formed into one solid block of nuclear matter. In such a collapsing process the radius of a star might decrease to one percent of its value within a few hours, and the enormous amount of gravitational energy liberated would be quite enough to explain the intense radiation of supernovæ. Under the pressure of radiation coming from the interior of the star, its outside layers will be blown away, to form the expanding shell that will surround the exploding star (Figure 49).

In spite of the great attractiveness of this explanation of the supernova explosion, it remains so far only an interesting hypothesis, since no rigorous theoretical treatment of such collapse problems has yet been performed. But it may be hoped that in the course of the next few years a satisfactory solution of this last remaining puzzle of stellar evolution will finally be found.

CHAPTER X

The Formation of Stars and Planets

STARS AS "GAS DROPS"

WE HAVE mentioned several times that in the early stages of their development all stars are extremely rarefied and comparatively cool spheres of gas, which become hot and luminous as the result of their gravitational contraction. Once upon a time, at the dawn of the universe, the stars must have been so dilute that they occupied all available space, forming a practically continuous gas. *Later, under the action of some internal instability, this continuous gas must have broken up into a number of separate clouds or, so to speak, "gas drops," which contracted into the stars as we know them at present* (Figure 50).

What were the physical conditions underlying this break-up of the continuous cosmic gas, and why does not the same thing happen to the ordinary atmospheric air, for example? It would be odd indeed if the air filling a room were to collect itself into many "air drops" and leave a vacuum in between them.

The difference between the two cases does not lie in any peculiar physical or chemical properties of the gas from which the stars were formed,* but is entirely due to

* Of course, the primordial gas was much hotter than the air, and consisted of vapours from all the different elements. But this would not make an essential difference in its general properties as a gas.

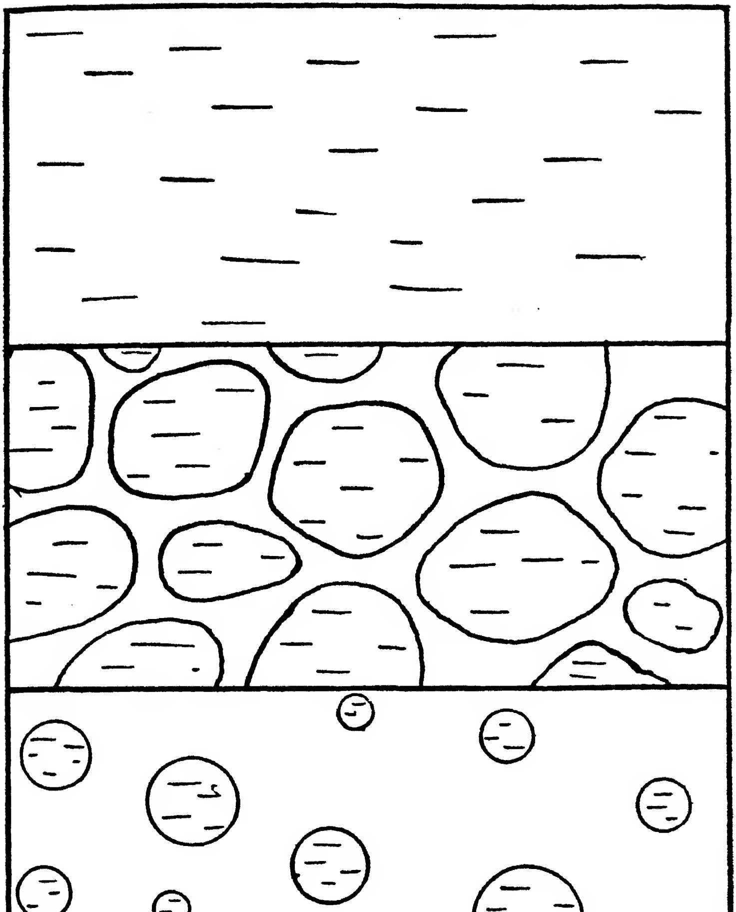


FIGURE 50
The formation of separate stars from a continuous gas.

the vast extent of interstellar space as compared with the volume of an ordinary room or even with the thickness of the earth's atmosphere. If, inside a room, or in the free atmosphere surrounding our globe, a part of the gas occasionally begins to concentrate in a certain region, the increased gas pressure at that point immediately disperses the concentration and brings the density to its normal value. Thus, the germs of the "air drops" never have the chance to develop into more serious concentrations.*

But, if such a germ is sufficiently large, it can be held together by the mutual gravitational attraction among its parts, and the forces of gravity will even cause its further concentration. The calculations of the British physicist and astronomer Sir James Jeans have shown that such germ formation must always take place if the gas is extended through a region of sufficiently large geometrical dimensions. In the case of atmospheric air, the diameter of a germ that could "hold itself together" would have to be many millions of kilometres, which explains why no "air drops" can be formed either in the room or in the thin atmospheric layer enveloping our globe. But in the dilute gas that long ago filled all infinite space, such concentrations must necessarily have taken place.

When all the matter that now forms the separate stars was uniformly distributed throughout space, its average density was very low, amounting to only 0.000,000,000,000,-

* We should note here, however, that even such small germs do play an important role in our atmosphere. The slight deviations from homogeneity in the air, due to this fluctuation of density, cause the scattering of the sunlight that passes through the atmosphere, and make possible the general illumination and blue colour of the sky above our heads. If the atmospheric air were absolutely homogeneous, the sky would always be black and the stars could be seen even in the daytime; neither would there be any beautiful sunsets.

000,000,000,1 times the density of water. At such low densities and at a temperature of several hundred degrees, the forces of gravity could break the gas into separate spheres, each with a diameter of about two or three light-years and a mass of about 1,000,000,000,000,000,000,000,000,000,000 kilograms. When further contracted by the forces of gravity, these gas drops would become the ordinary stars as we see them now in the sky.

It should be added that this process of star formation through the *gravitational* instability of large masses of gas could also lead, in some cases, to the creation of much larger bodies than the stars known to us. It can, however, be shown that the central temperatures and the nuclear energy production in the interiors of such "superstars" would make them absolutely unstable and cause their splitting into a number of smaller bodies.

DOES THE PROCESS OF STAR FORMATION CONTINUE AT PRESENT?

According to the best estimates, the age of the stellar universe is 2 billion years, which should also give us roughly the time when the break-up of the continuous distribution of primordial gas must have taken place. But is this process of star formation quite completed by now, or are some *new stars* (not novæ, but *really* new stars) being formed at the present time?

The study of different types of stars belonging to our system indicates quite definitely that some of them must be considerably younger than the rest of the universe. We have seen, for example, in Chapter VII, that the so-called *red giants* represent comparatively early stages of stellar evolution. It seems hardly probable that these stars can be

much older than a few million years, and we must conclude that their formation must have taken place during geological times. The most striking example of a star in the very early stages of its evolution is one we have already discussed, the infrared star ε Aurigæ I, which is probably still in the original contractive stage.

Then, too, the most brilliant stars of the main sequence, those known as *blue giants,* must also be relatively new stars. Indeed, owing to their extremely high luminosities, the *total* life expectancy of these stars must be comparatively short, and in our present state of knowledge it must be concluded that they represent a fairly recent addition to our stellar system. Such stars as, for example, 29 Canis Majoris or AO Cassiopeiæ produce 20,000 times more energy per gramme of their material than does our Sun, and are bound to run through all their original hydrogen content in not more than 5 million years. These stars were definitely not in the sky during the ages when giant reptiles crawled on the surface of our earth.

There is, of course, no lack of the diffuse gaseous material (*gaseous nebula*) still left in interstellar space, and we must conclude that *the process of star formation is still in progress,* although probably on a much smaller scale than during the epoch when the main body of stars was formed.

THE ORIGIN OF WHITE DWARFS

When we compare the ages of different types of stars with the estimated age of the whole stellar universe, we also meet with cases opposite to those of the red and blue giants, and in which the stars seem much older than they possibly could be. We have seen in Chapter VIII that the so-called *white dwarfs* are the stars already depleted of

their nuclear energy sources, and that they represent, in this sense, the evolutionary stage at which our Sun will arrive when it has exhausted all its original hydrogen content. But we have also seen that stars of the size of our Sun need several billions of years to attain this state, and that our Sun itself has since its birth used up barely one of the original 35 percent of its hydrogen content.

How does it happen, then, that such stars as the companion of Sirius, for example, have no more hydrogen in their interiors and are even now slowly dying? It is difficult to suppose that they did not have plenty of hydrogen from the very beginning, for the chemical elements in the universe seem pretty well mixed and distributed; on the other hand, they can hardly be older than the stellar universe itself. In short, *the stellar universe seems as yet too young to contain such old and decrepit stars as the white dwarfs*, and the presence of the companion of Sirius in the stellar family is no less surprising than would be the appearance of a white-bearded man in one of the cribs of a maternity ward.

It seems to the author that the only reasonable explanation of the existence of white dwarfs of the observed mass in the present stage of the development of the stellar universe is the hypothesis that *these stars have never been young,* and represent only the fragments formed by the collapse of heavier and more rapidly evolving stars. The very massive and luminous stars created at the very beginning of the stellar universe must have exhausted their hydrogen content and started their ultimate contraction long before the present time. We have seen in a previous chapter that the contraction of such stars, many times heavier than our Sun, leads most probably to a sudden col-

lapse of their bodies (see Zwicky's explanation of supernovæ), with a consequent split into several smaller pieces. *These fragments, formed by stellar explosions in the distant past, may account for the white dwarfs* observed at the present time in our stellar system.

WHAT ABOUT PLANETS?

When people first began to think about the origin of the world along scientific lines, their main interest was concentrated upon problems concerned with the formation of our earth and the other planets of the solar system. And it is a curious thing that, even at present, when we know so much about the origin of different types of stars and seriously discuss questions relating to the birth of the entire universe, the problem of the earth's formation is not yet quite settled.

More than a century ago the great German philosopher Immanuel Kant formulated the first scientifically acceptable hypothesis about the origin of our planetary system, a hypothesis that was further developed by the equally famous French mathematician Pierre Simon de Laplace. According to this hypothesis, the several planets were formed from gaseous rings detached by centrifugal force from the main body of the Sun during the early stages of its contraction (Figure 51). In view of our present knowledge this attractive and simple hypothesis will not stand up under serious criticism.

First of all, mathematical analysis has shown that any gaseous ring that might be formed around the contracting and rotating Sun would never condense into a single planet but would rather give rise to a large number of small bodies analogous to the rings of Saturn.

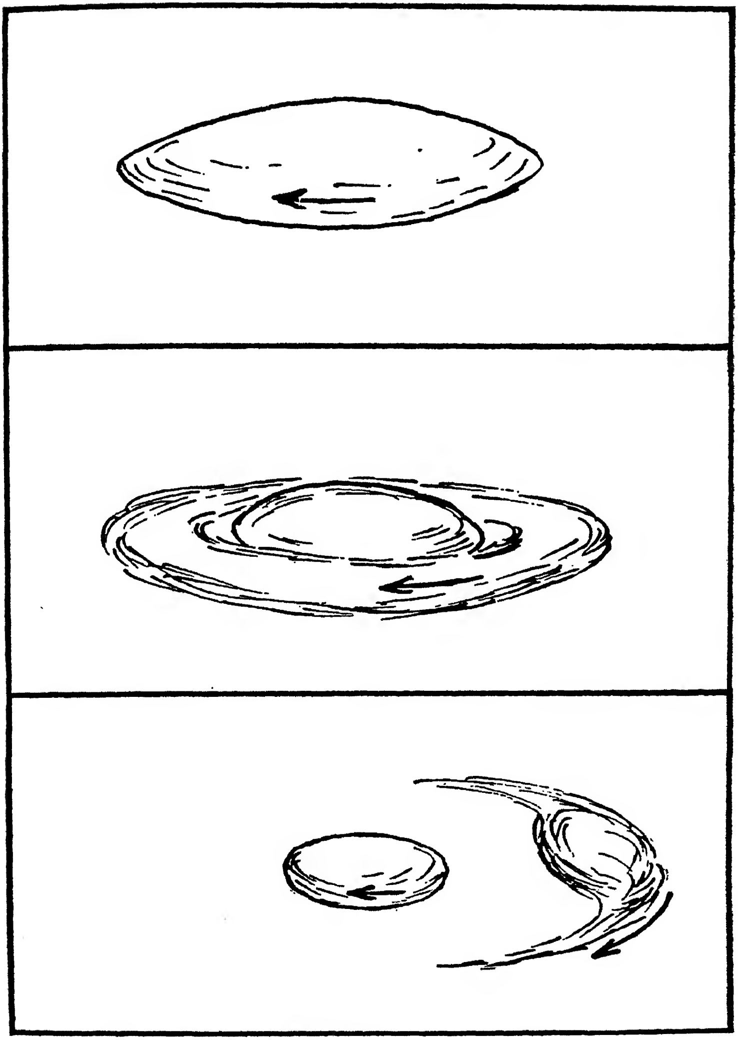


FIGURE 51
The (incorrect) Kant-Laplace hypothesis of the formation of planets.

The second, and still more serious, difficulty presented by the Kant-Laplace hypothesis consists in the fact that 98 percent of the total rotational momentum of the solar system is associated with the motion of the major planets, and only 2 percent is accounted for by the rotation of the Sun itself. It is impossible to see how such a high percentage of rotational momentum could be concentrated in the ejected rings, leaving practically nothing with the original rotating body. It seems, therefore, necessary to assume (as was first done by Chamberlin and Moulton) that the rotational momentum was put into the system of planets from the outside and to consider *the formation of the planets as due to an encounter of our Sun with some other stellar body of comparable size.*

We must imagine that once upon a time, when our Sun was a lonely body without its present family of planets, it met another similar body travelling through space. For the birth of planets no physical contact was necessary, since the mutual forces of gravity even at comparatively great distances can have caused on the bodies of both stars the formation of huge elevations extending toward each other (Figure 52). When these elevations, actually giant tidal waves, surpassed certain limiting heights, they must have broken up into several separate "drops" along the line between the centres of the two stellar bodies. The motion of the two parent stars relative to each other must have given to these rudimentary gaseous planets a vigorous rotation, and when the parents parted they were each enriched by a system of rapidly rotating planets. The tidal waves on the surface of the stars must also have forced them to rotate slowly in the same direction as their planets, which explains why the rotation axis of our Sun so closely coincides with the axis of the planetary orbits.

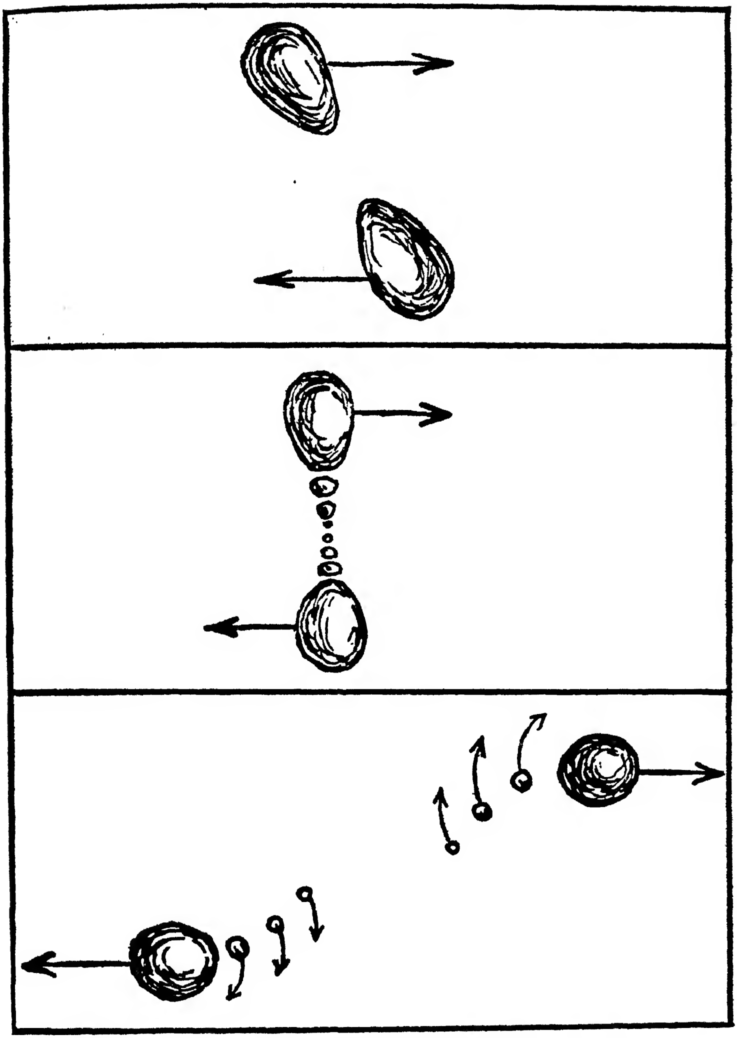


FIGURE 52
The "hit-and-run" hypothesis of the formation of planets.

It is interesting to think that somewhere in interstellar space moves a star responsible for the birth of our planetary system, and carrying along some of the half-brothers and half-sisters of our earth. But since the birth of our planetary system took place a few billions of years ago, our Sun's spouse must be very far away by now, and could be almost any star observed in the sky.

This "hit-and-run theory" of the formation of our planetary system also leads to some difficulties, however, if we inquire into the chances of such a close encounter between two stars. From the tremendously great distances between stars and their comparatively small radii it is easy to calculate that, during the few billion years that have passed since their formation, the chance of such an encounter for each individual star is only one in several billions. Thus we should be forced to the conclusion that planetary systems are very rare phenomena, and that our Sun must be extremely lucky to have one. It may also mean that, among all the billions of stars forming our stellar system, the Sun and its spouse are probably the only ones to have a planetary family!

It is true, of course, that no telescope yet constructed is strong enough to answer directly the question as to the possible existence of other planetary systems, even in the case of the nearest stars. But it would be extremely awkward if the planetary system of our Sun were to represent so rare a phenomenon, especially in view of the large observed number of double (and even sometimes triple) stars, the origin of which is not much easier to understand than the origin of the systems of smaller satellites.

We can, however, escape all these difficulties if we suppose that the formation of planets took place during the

early stages of the development of our universe, soon after the formation of the stars themselves. We shall see in the next two chapters that our universe is in a state of ever-progressing expansion, from which it follows that in the remote past the distances between individual stars must have been considerably smaller than they are at present. During that epoch, near-collisions between stars must have represented a much more common event, and *each star was given a fair chance to acquire a planetary system of its own.* Many of these stellar encounters may also have led (with the help of a third body) to the permanent binding of the passing couples and the creation of what we now observe as binary systems.

CHAPTER XI

Island Universes

THE MILKY WAY

ON CLEAR nights, we can easily see a faint luminous band stretching across the sky from one horizon to the other. To the vivid imagination of ancient astronomers, this band presented itself as a flow of milk escaping from some heavenly Cow (though there does not seem to have been any constellation of that name), and it therefore received the name of the *Galaxy* or, in English, the *Milky Way*. The early telescopic observations of the famous astronomer Sir William Herschel reinforced this metaphor by showing that, just as ordinary milk consists of minute particles of fat suspended in a more or less transparent liquid, so does the celestial Milky Way consist of an immense number of very faint stars individually indistinguishable by the naked eye (see Plate XII).

The fact that the stars composing the Galaxy fall within a more or less regular belt that encircles the sky gave Herschel the ingenious idea that this collection of stars had the shape of a rather flattened disk, something like a thin watch, and that our Sun was situated somewhere in the interior of the space occupied by it. As must be clear at once from Figure 53, which represents Herschel's view of the galactic system, we shall find comparatively few stars in the direction perpendicular to the main plane of the disk and a great number of them in the direction of

this plane. Most of the stars seen in the direction of the plane are very distant from our point of observation; and their relative visual faintness, together with their large number, gives that impression of continuously distributed luminosity which is observed by the naked eye. This picture of the stellar universe, proposed by Herschel more

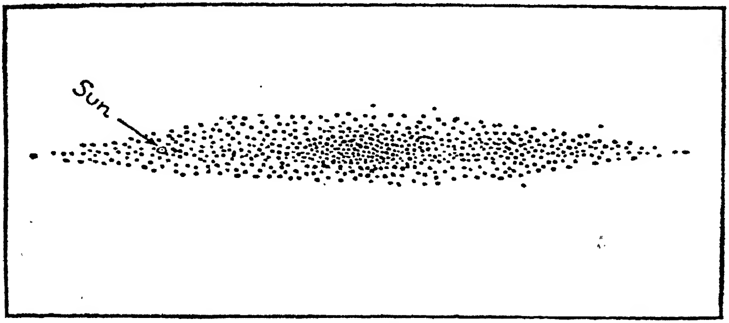


FIGURE 53
A schematic view of the stellar system of the Milky Way, showing the excentric position of the Sun.

than a century ago, formed a solid basis for all later studies of the universe on a large scale.

THE NUMBER OF STARS IN THE SKY

Notwithstanding the common expression, "as many as there are stars in the sky," the number of stars actually seen by the naked eye is not at all large. In fact, the total number of such stars, including those of both the northern and the southern hemispheres, amounts to only a little more than 6000; and at any one time, taking into account the poor visibility near the horizon, hardly more than 2000 can be seen.

The situation changes, however, quite significantly when

we count also those stars that can be seen through powerful telescopes, and the phrase of common speech mentioned above becomes more reasonable if we understand it in terms of the present astronomical evidence. *The total number of stars in our galactic system,* including the most distant and faint ones, *is estimated* by the Dutch astronomer Kapteyn, to whom we owe the most careful study of the Milky Way, *to be about 40 billions,* which is quite a lot of stars.

Of course, all the stars in the Milky Way do not have personal names, such as Sirius or Capella. It is not so much that one could not find enough names to go around among the members of this 40-billion-strong family, for the number of eight-letter words that could be formed with the twenty-six of the alphabet would suffice. It would simply take too long to christen every member of our Galaxy; at the rate of one new name per second, we should need about 1700 years to complete the list.

THE DIMENSIONS OF OUR STELLAR SYSTEM

The distance to Sirius is 52,000 billion miles, and it takes light, travelling at 186,000 miles per second, eight years to traverse it. But Sirius is comparatively near; to come to us from the most distant members of the galactic system, light often requires as much as several thousand years. Indeed, astronomers save themselves the trouble of dealing in such large numbers by expressing these stellar distances in *light-years.**

After careful measurements, Kapteyn came to the conclusion that the 40 billions of stars in our Galaxy are dis-

* A light-year is equivalent to 9,463,000,000,000 kilometres or 5900 billion miles.

tributed within a *lens-shaped space measuring about 100,000 light-years in diameter and 10,000 light-years in thickness*. The limits of this lenticular Galaxy are, of course, not very sharp, since the distribution of stars becomes more and more sparse as we go outward from the central regions. It is quite possible that a few stars may still be found at distances several times greater than those indicated above.

Our own Sun, together with its system of planets, is situated not far from the rim of the galactic lens, rather close to the equatorial plane, and about 30,000 light-years from its centre. This centre of the Galaxy, which should be expected to show a much greater concentration of stars, and hence considerably greater intensity of light, is to be found in that part of the Milky Way that passes through the constellation Sagittarius (see the map of the stellar sky on the inside cover of the book). Unfortunately, some dark interstellar clouds,* formed by large masses of cool gas that were left over after the creation of the stars, hang in the space between the galactic centre and our Sun, making observation of this most interesting region quite impossible.

THE MOTION OF STARS WITHIN THE GALAXY

In ancient astronomy, the stars that composed the different constellations in the celestial sphere were called "fixed stars," in contrast to the "wanderers," or "planets," which move among the fixed stars with comparative rapidity. We know now that these so-called "fixed stars" also move through space, and indeed with velocities even greater

* One of the so-called gaseous nebulæ. See pp. 187–188 above and compare Plate X.

than those of the planets. Owing, however, to the enormous distances that separate us from these stars, their high absolute velocities result in relatively minute angular changes of their observed positions. But photographs of the stellar sky taken several years apart do permit us now to note these slight changes of position, and to predict how our sky will look in the very distant future.

In Figure 54, for instance, we give the changes that are destined to take place in the familiar constellation of the Great Bear, more commonly known as the Dipper. A period so short, astronomically, as a few hundred thousand years is enough to produce a complete change in the general appearance of the sky. We thus see that, when the Neanderthal caveman hunted bears and mammoths over the face of Europe tens of thousands of years ago, the stellar pattern above his head was quite different from what we know at present. It is a pity, therefore, that, when he covered the walls of his caves with artistic pictures of the chase, it never occurred to prehistoric man to draw an image of the stellar sky; it would most certainly have saved modern astronomers a lot of trouble.

Incidentally, we may remark that, although the motions of the different stars through space are on the whole rather irregular and independent of each other, there are many instances in which the stars that happen to form a given constellation seem to be moving together. In the case of the Great Bear, for example (Figure 54), five of the seven stars are evidently moving in the same direction, and the estimate of their relative distances indicates, moreover, that they are situated rather near to each other. The other two stars, which are responsible for the dipper-shape of

the whole constellation, are obviously not connected with the system. They are moving in a quite different direction

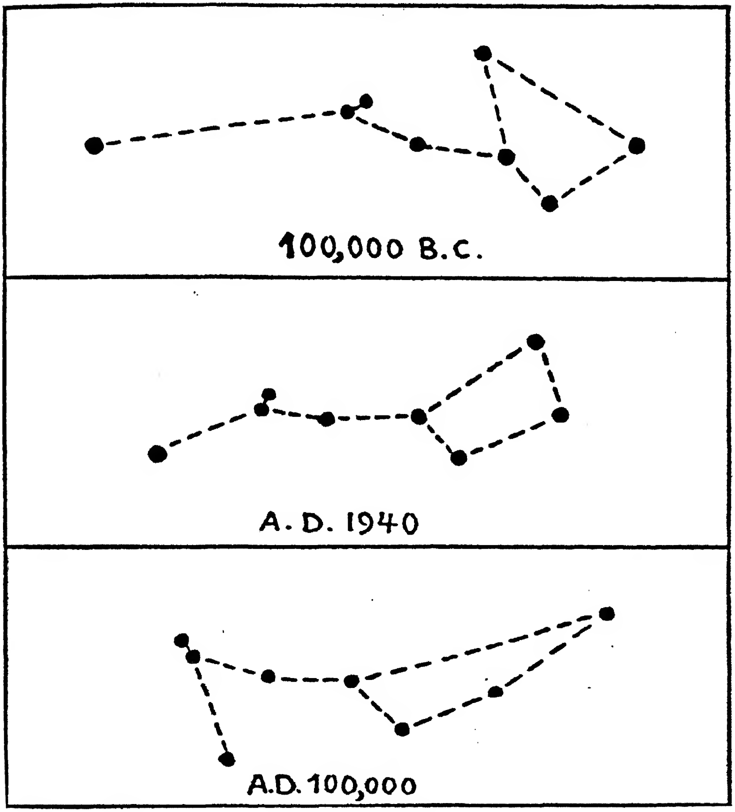


FIGURE 54
Changes in the constellation of the Great Bear (the Dipper) in 200,000 years.

and, at the time of prehistoric man, would probably not even have been thought to be related to the rest of the

group. Another interesting example of the changes to be expected in a well-known grouping of stars is given by the constellation Scorpio, shown in Figure 55.

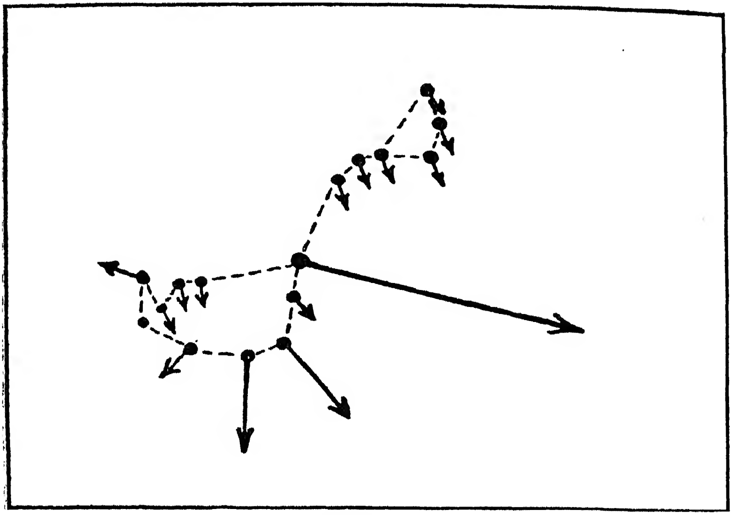


FIGURE 55
The constellation Scorpio and the future changes (arrows) in the positions of its stars, 100,000 years hence.

THE VELOCITIES OF STARS

Knowing the angular displacements of stars due to their motion, and also their absolute distances from us, we can easily calculate their linear velocities perpendicular to the line of sight. *These linear velocities average about 20 kilometres per second,* although in some cases they are found to be as high as 100 kilometres per second. Our own Sun is moving with a velocity of 19 kilometres per second toward a point situated somewhere in the constellation Hercules.

Although stellar velocities may seem very high from

man's point of view, they are rather small when compared with the giant distances that separate the stars scattered through space. If our Sun were moving directly toward one of its nearest neighbours, α Centauri, separated from us by only 4.3 light-years, it would take them about 70,000 years to collide. But we need not fear so unpleasant an accident, for the stars are so thinly distributed through space that the chances of such a collision are negligibly small. In fact, it has been calculated that only a very few such collisions can have taken place in the whole stellar universe during the 2 billion years of its life.

THE ROTATION OF THE GALAXY

Besides the irregular random motion of the individual stars that form our Galaxy, astronomical observations have also found that this whole lenticular system is slowly rotating around its central axis. According to the latest estimates, the rotation of the Galaxy amounts to about 7 angular seconds per century, from which we may conclude that, during the whole of geological time, our Galaxy has made five or six complete turns.

This may not seem like much, but one must not forget that, owing to the giant dimensions of the galactic lens, this angular rotation velocity actually corresponds to linear velocities on the periphery of many hundreds of kilometres per second. It is most probably this rotation that is responsible for the flattened shape of the Galaxy, just as the rotation of the earth is responsible for its ellipsoidal shape.

THE AGE OF THE MILKY WAY

If we remember that our Sun is only one of the numer-

ous company of the galactic system, we must conclude that the age of the Galaxy cannot be less than the age of the Sun, and must amount to at least a few billions of years.

The study of stellar motion permits us also to put an upper limit on the possible age of our Galaxy. It can be shown that, under the forces of mutual gravitational attraction, a collection of stars moving within a limited space must sooner or later attain a definite distribution of velocities that is quite analogous to the Maxwell distribution of gas molecules (compare Chapter II). Statistical calculations applied to the stars forming the system of the Milky Way indicate that in this case the Maxwell distribution of velocities should be reached within a period of about 10 billion years. Since, according to astronomical evidence, such a distribution has not yet been reached by a large margin, we must conclude that *the actual age of the stellar universe lies somewhere between 1.6 and 10 billion years.*

OTHER "GALAXIES"

For a long time observational astronomy has known of the existence of a large number of elongated nebulous objects distributed more or less uniformly throughout the stellar sky. But only in comparatively recent times has it been established beyond doubt that these so-called *elliptic or spiral nebulæ* do not belong to our system of the Milky Way, but represent autonomous stellar systems, analogous to our own and situated at extremely great distances from it.

The observed shapes of these remote stellar systems correspond exactly to what our own system must look like from the outside, according to the universally accepted view of Herschel. In Plates XIII, XIV, XV, and XVI we

PLATE XIII. The central part of our nearest island universe, the spiral nebula in Andromeda, only about 680,000 light-years away. The stars in the foreground belong to our own Galaxy. (See p. 216.) (Mt. Wilson photograph.)

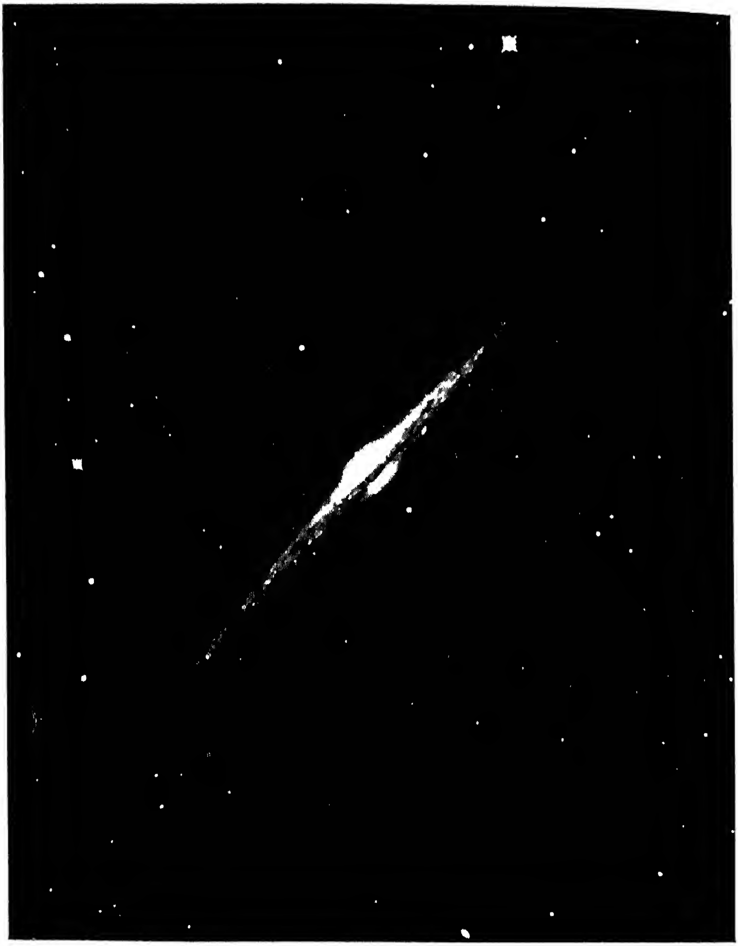


PLATE XIV. The spiral nebula in Coma Berenices, a distant island universe seen on edge. Note the ring of darker matter encircling this nebula. (See p. 220.) (Mt. Wilson photograph.)

give the photographs of several stellar systems of this kind, taken through the powerful telescope of the Mount Wilson Observatory. These photographs make apparent the lenticular shape of the extragalactic "nebulæ" and also indicate the presence of somewhat irregular spiral arms winding around the central elongated bodies. Not all extragalactic nebulæ possess these spiral arms, however, and a number of them have regular shapes of more or less flattened ellipsoids.

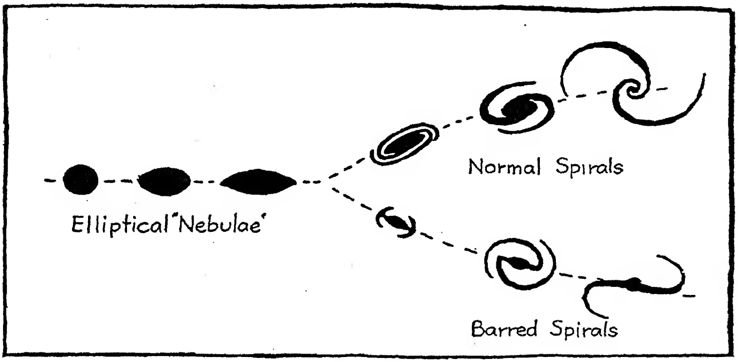


FIGURE 56
Hubble's classification of extragalactic "nebulæ."

In Figure 56 the reader will find a schematic representation of the various observed shapes of these nebulæ, based on the observations of the Mount Wilson astronomer, E. Hubble, to whom we owe most of our information concerning these distant island universes. When observed through not very strong telescopes, they seem to be continuous luminous masses of gas (hence their name "nebulæ"); but the 100-inch telescope of the Mount Wilson Observatory reveals that the outer arms at least are actually made up of billions of separate stars, very similar to the mem-

bers of our own stellar system. But even in these powerful enlargements, the central bodies of the nebulæ are not resolved into separate stars. Their stellar character may be proved only by somewhat more indirect evidence, which will be discussed in a following section.

DISTANCES AND DIMENSIONS OF EXTRAGALACTIC NEBULÆ

The distances separating us from the other island universes are so immensely large that the ordinary astronomical methods for measuring distances (e.g., parallax estimates) completely fail us. This is why, until only rather recently, these objects were erroneously located somewhere among the stars of the Milky Way.

The first measurements were made possible, in the case of the nebula in Andromeda (Plate XIII), only after it was shown that its spirals consisted of numerous separate stars, which included among them several cepheid variables. We have already seen in Chapter VII that these peculiar stars are characterized by a regular pulsation, and that their pulsation periods are directly related to their luminosity. By observing the periods of cepheid variables in the spiral arms of the Andromeda Nebula, one could therefore compute their absolute luminosity; and by comparing their absolute luminosity with their observed brightness one could now estimate their distance by the application of the simple inverse-square law.

All the cepheids that have been found in the Andromeda Nebula lead to about the same result, indicating *a distance from us of 680,000 light-years.* The geometrical dimensions of the Andromeda Nebula come out to about the same as, or slightly smaller than, those of our Milky Way, and its

total luminosity is estimated to equal 1.7 billion times that of our Sun.

The Great Andromeda Nebula is one of the nearest neighbours of our galactic system, and so its tremendous

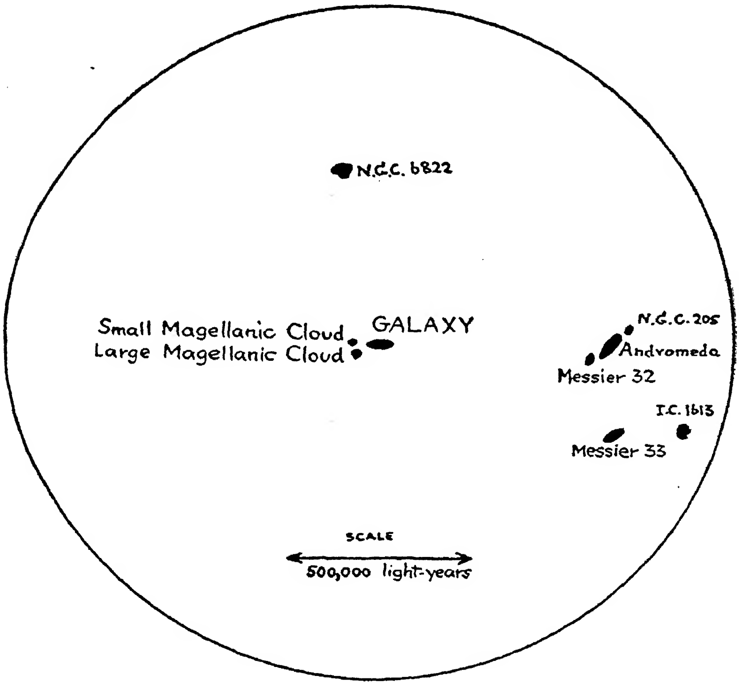


FIGURE 57
The Galaxy and its nearest neighbours in space.

distance gives us some inkling of the vastness of the empty spaces of the universe. Other neighbours include another spiral, two elliptic, and two irregularly shaped nebulæ. Their respective distances and relative positions are schematically represented in Figure 57.

In the neighbourhood of the Andromeda Nebula, observation has revealed the presence of two "satellites" of this remote stellar world. These also represent large accumulations of stars, hundreds of millions of them, revolving around the Andromeda Nebula like a swarm of bees.* It would certainly be unfair if our Milky Way did not also have satellites of its own; and in fact it has two of them. Being comparatively close to us (85,000 and 95,000 light-years away), these can easily be seen by the naked eye. They were first described by the Portuguese explorer Ferdinand Magellan; thus, on our stellar maps we have two *Magellanic clouds,* just as on our terrestrial maps we have Magellanic Straits.

Besides these near neighbours, telescopic observation has revealed a very large number of more distant stellar islands of the same kind. Varying slightly in shape and size, these "stellar otherworlds" are scattered throughout the vast spaces of the universe as far as the strongest telescopes permit us to see. According to Hubble, the large telescope of the Mount Wilson Observatory penetrates into regions of space *500 millions of light-years away,* and finds there spiral nebulæ quite similar to Andromeda's or our own Milky Way. The total number of the stellar islands that can be seen within this distance is about 100 million, and there are probably still more, too far away even for the 100-inch telescope.

EXTRAGALACTIC "NEBULÆ" ARE NOT NEBULÆ

On page 215, we promised to give the reader proof of the statement that *the so-called extragalactic "nebulæ" are not giant masses of continuous gas but consist of large*

* See Plate XVI for an example of a satellite of a spiral nebula.

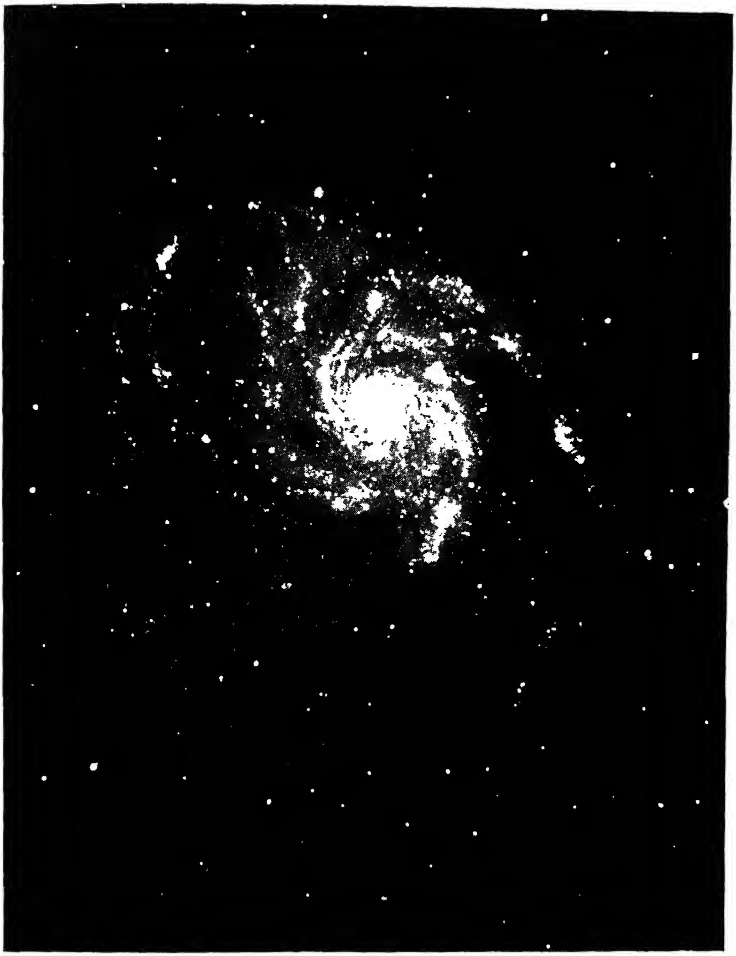


PLATE XV. Spiral nebula in Ursa Major, another distant island universe, seen from above. Note the clusters of stars in the arms. (See p. 220.) (Mt. Wilson photograph.)

Plate XVI. Spiral nebula in Canes Venatici, showing a satellite at the end of the lower arm. (See p. 218.) (Mt. Wilson photograph.)

numbers of stars similar to those of the Milky Way. As a matter of fact, the proof is rather simple. It is based on observations which show that the spectral character of the light emitted by these "nebulæ" is very similar to that of the light emitted by our Sun. We know from the discussion in Chapter VI, therefore, that the surface temperature corresponding to such light emission cannot be much different from the surface temperature of the Sun and must amount to several thousand degrees.

If these "nebulæ" were really giant masses of continuous gas having the same surface temperature as our Sun, the total light emission would be proportional to their surface area, that is, to the square of their linear dimensions. And since the average diameter of these "nebulæ" is about a billion times larger than the diameter of our Sun, we should expect that their total luminosity would be a *billion billion times larger.* But we have just seen that the actually observed luminosity of the Andromeda Nebula is considerably smaller than that, amounting to only 1.7 billion times that of the Sun. We must inevitably conclude, therefore, that the light comes not from the entire surface, but only from a large number of small luminous spots (see Figure 53), the total surface area of which hardly comes to one-billionth of the total surface area of the nebula. This is just what we would expect if the "nebulæ" were made up of separate normal stars.

THE ROTATION OF EXTRAGALACTIC NEBULÆ AND THE ORIGIN OF SPIRAL ARMS

It has been mentioned that the statistical study of the motion of the stars of the Milky Way shows that our stellar system is slowly rotating around its central axis. A similar

rotation has also been found in the case of other stellar systems. The Doppler effect on the two opposite ends of an extragalactic nebula seen on edge (see Plate XIV) always indicates that one end is approaching us while the other is receding. The Great Nebula of Andromeda, for example, makes one complete revolution in several hundred million years, spinning with about the same angular velocity as our Milky Way.

It is easy to see that the rotation is responsible for the elliptical shape taken on by these stellar accumulations, but it is more than probable, too, that the spiral arms are also due to it. The current theory, proposed by Sir James Jeans, supposes that the spiral arms are formed by the material expelled from the very rapidly rotating equatorial plane of the nebulæ (see Plate XV). Although Jeans's view seems to give a correct explanation of the origin of these interesting celestial forms, some difficulties have been encountered in the attempts to provide a more detailed picture of the process. In particular, the existence of two kinds of spiral arms, as indicated in Figure 56, still represents an unsolved problem of theoretical astronomy.

CHAPTER XII

The Birth of the Universe

NEBULÆ RUNNING AWAY

THE study of the innumerable galaxies scattered through the vast spaces of the universe brought the foremost man in nebular research, Dr. E. Hubble, to an extremely interesting and puzzling conclusion. Measuring the radial velocities* of these distant stellar systems, he noticed that they almost all *showed a definite tendency to recede from us rather than to approach us.*

This was not so true of the extragalactic nebulæ closest to us, for these exhibited a rather arbitrary distribution of velocities, with almost as many of them approaching us as there were receding; in particular, the Great Andromeda Nebula is moving toward us at a velocity of 30 kilometres per second. But even in these cases the approach velocities are always somewhat smaller than the velocities of recession, showing a general tendency of the stellar islands to increase their distance from our Galaxy.

Also, as we go further and further out toward the more distant stellar islands, the recession velocity becomes greater and greater, completely overbalancing any contrary effect of the irregularity of individual systems (see Figure 58).

* The radial velocities of these distant objects, that is, the velocities along the line of sight, can be directly estimated from the observed Doppler shift of the lines in their spectra. Because of the enormous distances, the *proper motion* of extragalactic nebulæ, perpendicular to the line of sight, cannot be measured.

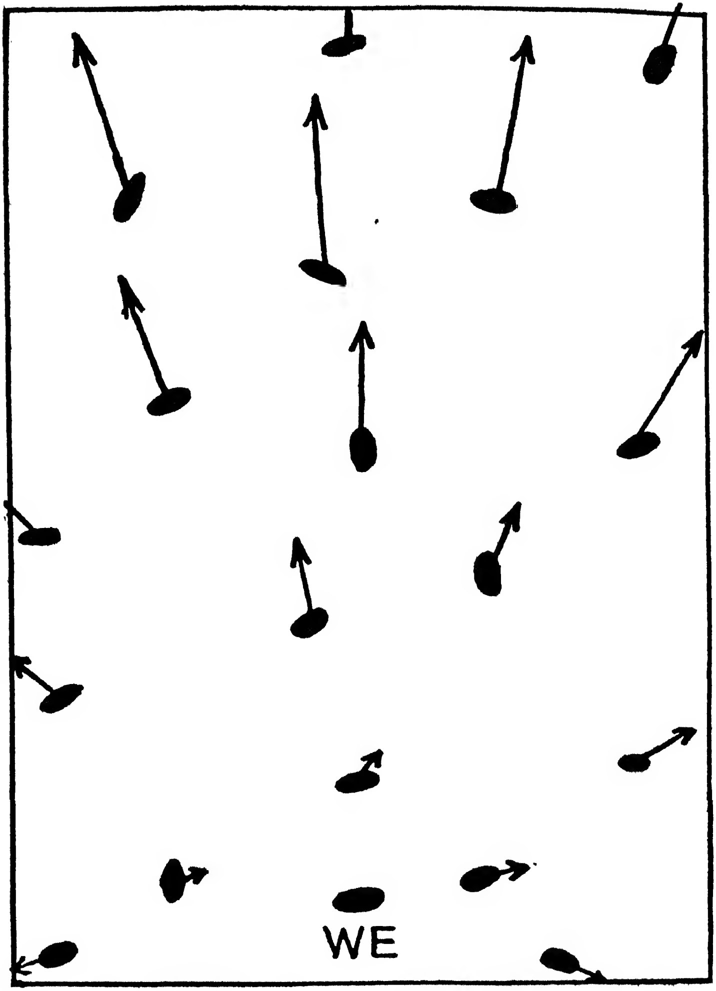


FIGURE 58
Extragalactic nebulæ running away from us. Note the direction and the length of the velocities.

Without a single exception, all the very distant stellar islands are running away from the earth, and the farther they already are the faster they go. Hubble's measurements demonstrate that these recession velocities increase in direct proportion to the distance, varying from a few hundred miles per second for the neighbouring nebulæ up to *60,000 miles per second* (one-third the velocity of light!) for the most distant but still visible ones.

AN EXPANDING UNIVERSE

But is it not too much to suggest that our poor little earth, with its handful of inquisitive astronomers, frightens all these giant stellar worlds to such an extent that they rush away in all possible directions? Does this point of view not represent a return to the long-abandoned Ptolemaic system of the world, with its geocentric conception?

Not at all, for the extragalactic nebulæ are not running away from our Galaxy particularly, but in reality from one another. If we paint a number of more or less equidistant dots on the surface of a rubber balloon, which we then blow up (Figure 59), the distance from any given dot to all the others will regularly increase, so that an insect sitting on one of the dots will receive the definite impression that all the other dots are "running away" from it. Moreover, the recession velocities of the different dots on the expanding balloon will be directly proportional to their distances from the insect's observation point.

This illustration should make it quite clear that the phenomenon observed by Hubble may be interpreted as due to *a general uniform expansion of the space occupied by the extragalactic nebulæ.* We must point out that only the distances between different stellar islands, and not their

proper geometrical dimensions, increase in this process of expansion. Two billion years from now, all the stellar islands will have about their present size, but they will be twice as far from one another. On the other hand, according to these estimates, *2 billion years ago the distances*

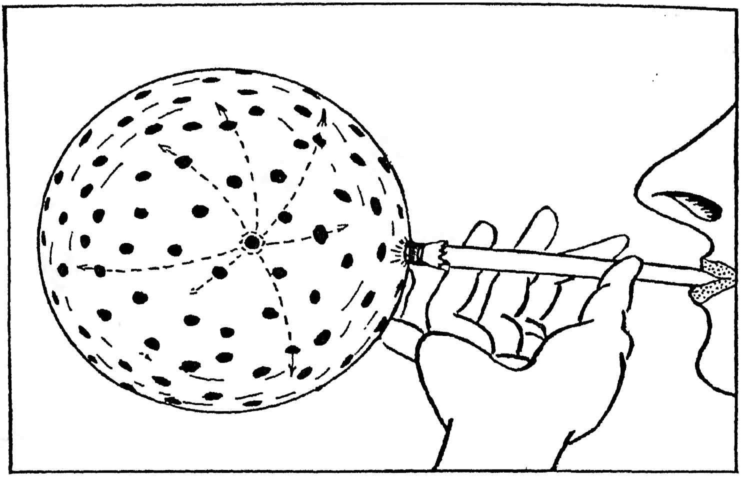


FIGURE 59
The dots run away from one another when the rubber balloon is expanding.

between the stellar islands must have been so small that the nebulæ constituted a practically undifferentiated collection of stars uniformly distributed throughout the universe (Figure 60).

We see, then, that the process in which the separate galaxies are formed is somewhat analogous to the process that has led to the formation of individual stars, but with the difference that, whereas the stars were formed from ordinary gas consisting of molecules, the formation of galaxies

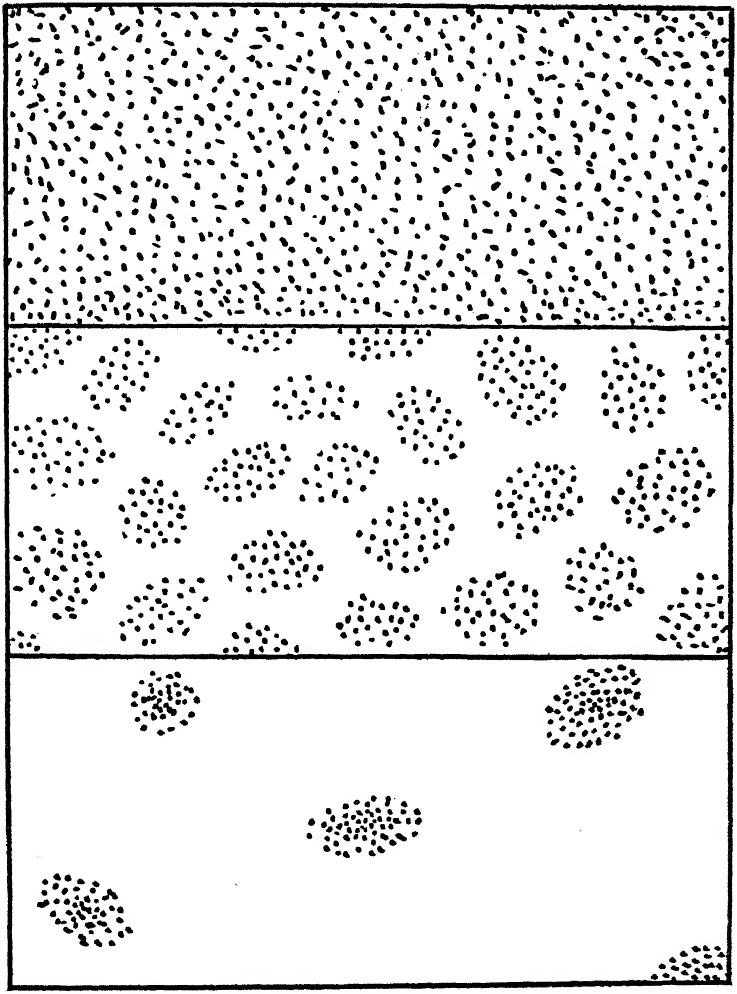


FIGURE 60
Formation of island universes, through the expansion of space, from the uniform distribution of stars.

corresponds to the "coagulation" of a "stellar gas," the particles of which are represented by separate stars.

Before the separate galaxies were pulled away from one another by the progressive expansion of the universe, very strong gravitational interactions must have taken place among those giant groups of stars. In a way very similar to that which leads to the formation of planetary systems in the case of individual stars (Chapter X), such interactions must have supplied the newborn stellar islands with a certain amount of angular momentum, and may perhaps also have drawn from their bodies those long ribbons of "stellar gas" which we now observe as their spiral arms.

WHICH ARE OLDER: STARS OR GALAXIES?

We have just suggested that the galaxies were formed from a continuously distributed multitude of stars, which of course presupposes that stars are older than galaxies. But is this correct? Why cannot one suppose, as was done by Sir James Jeans, that the process actually went the other way around? According to him, the primordial gas filling the universe was first broken up into giant *gaseous* nebulæ, and the process of star formation began only when these nebulæ became entirely separated from one another. What can be said against this alternative hypothesis?

The question of the relative ages of stars and nebulæ is not unlike the famous problem concerning the hen and the egg; it is unfortunately rather complicated, and can hardly be discussed without going into much too much detail. We shall have to content ourselves, therefore, with saying that, according to recent investigations by the author and his colleague Edward Teller, all the observational evidence indicates that the stars already existed when

the process of the formation of galaxies was just beginning.

This conclusion possesses definite advantages over Jeans's point of view, and permits us not only to give a satisfactory explanation of the processes underlying the formation of galaxies, but also to calculate their distances and dimensions in fair agreement with the observations. The reader who wishes to learn more about this important controversy in cosmogonic theory must be referred to the special literature devoted to these problems.

THE EARLY STAGES OF EXPANSION AND THE CREATION OF RADIOACTIVE ELEMENTS

If we now look backward in time, reversing the process of progressive expansion, we are obliged to conclude that, a long, long time ago, before the galaxies or even the separate stars were formed, both the density and the temperature of the primordial gas that filled the universe must have been extremely high. Only with the progressive expansion did the density and the temperature fall sufficiently low to permit the degradation of the primordial gas and the formation of separate stellar bodies. Theoretically, the densities and temperatures corresponding to the very earliest evolutionary stage of the expanding universe were higher than anything we can imagine, and . . .

"Enough!" the reader has by now certainly exclaimed. "After all, this book is supposed to be based on certain physical realities. But all this talk of the universe's being formed from a superdense and superhot gas sounds very much like metaphysical speculation!"

There is, however, a good physical reality that strongly supports, if it does not actually prove the truth of, these seemingly metaphysical speculations about the very first

stages of the development of our universe. This reality consists in the existence of the ordinary radioactive elements, such as uranium and thorium, which are unstable and must, therefore, have been formed within a certain finite time interval from now. The life periods of these particular radioactive elements (4.5 billion years for uranium and 16 billions for thorium), together with their comparative abundance at the present time, strongly suggest that *their origin dates no further back than a couple of billion years.* This coincides roughly with the probable date of the creation of the universe from the primordial superdense gas, as given by the observational evidence on the present rate of expansion.

Furthermore, the recent investigations of the young German physicist Carl von Weizsäcker have definitely proved that the formation of such heavy elements as uranium and thorium could have taken place only under the physical conditions of enormously high densities and temperatures—densities several billions of times larger than that of water and temperatures of several billions of degrees Centigrade. As such extreme conditions could not be found even in the central regions of the hottest stars, we are forced to look for them in the early superdense and superhot stages of the universe.

These diverse facts add up to give us a clear picture, according to which *the formation of radioactive elements must have taken place during the "prehistoric" stages of the universe.* Thus, the luminous hands of our wristwatches are fed by energy that was squeezed into atomic nuclei in the epoch preceding the formation of the stars and of the universe as we know it at present.

THE INFINITY OF SPACE

How large was the universe when, instead of being so very dilute, as it is now, its density surpassed the density of water by a factor of many billions? Was it perhaps so small that it could have been squeezed in a fist, if there had been fists at that time? The answer to this question depends on whether our universe is finite or infinite. If the universe has finite dimensions, let us say 10 times as great as the distance to the most remote visible nebula, its diameter at the time the radioactive elements were formed must have been only 10 times larger than the orbit of Neptune! But if the universe is infinite, it would also have been infinite no matter how strongly it was squeezed.

The problems of the finite and infinite properties of space, and the closely related questions about spatial curvature, belong to the domain of the general theory of relativity and, strictly speaking, do not enter into the scope of the present book.* We shall, therefore, have to be satisfied with the observation that, according to the most recent investigations, our space seems to be infinite and rapidly expanding into infinity. So much the better!

* A discussion of curved spaces and the problems of spatial expansion may be found in the author's book, *Mr. Tompkins in Wonderland* (Macmillan, 1940).

Conclusion

BEFORE closing this book and turning to a more amusing kind of mystery story, the reader would probably like to refresh his mind on its main conclusions and to have reviewed in a few sentences and in more strictly chronological order the picture it presented of the evolution of our universe in the light of modern science.

The story begins with space uniformly filled with an unbelievably hot and dense gas, in which the processes of the nuclear transformation of the various elements went on as easily as an egg is cooked in boiling water. In this "prehistoric" kitchen of the universe, the proportions of the different chemical elements—the great abundance of iron and oxygen and the rarity of gold and silver—were established. To this early epoch also belongs the formation of the long-lived radioactive elements, which even at the present time have not yet quite decayed.

Under the action of the tremendous pressure of this hot compressed gas, the universe began to expand, the density and the temperature of matter slowly declining all the while. At a certain stage of the expansion, the continuous gas broke up into separate irregular clouds of different sizes, which soon took on the regular spherical shapes of individual stars. The stars were still very large, much larger than they are now, and not very hot. But the progressive process of gravitational contraction diminished their diameters and raised their temperatures. The frequent mutual collisions among the members of this primitive stellar family led to the formation of numerous planetary systems,

and in one of these encounters our earth was born.

While the stars grew hotter and hotter, and their planets —being small and unable to develop the high central temperatures necessary for thermonuclear reactions—covered themselves with solid crusts, the "stellar gas" uniformly filling all space continued to expand, and the distances between the stars began to approach their present values.

At another stage of the expansion, corresponding to the average concentration still to be found within individual galaxies, the "stellar gas" broke up into separate giant clouds of stars. While these stellar islands were still close to one another, their mutual gravitational interaction led in many cases to the formation of the odd-looking spiral arms and supplied them with a certain amount of rotational momentum.

By that time most of the stars that made up these receding stellar islands had become sufficiently hot in their interior regions to start off various thermonuclear reactions between hydrogen and other light elements. First deuterium, then lithium, beryllium, and, finally, boron were turned into "ashes" (nuclear "ash" being the well-known gas helium); and, passing through these different phases of "red giant" development, the stars approached the main and longest part of their evolution. When no other light elements were left, the stars began to transform their hydrogen into helium through the catalytic action of the phœnix-like elements, carbon and nitrogen. Our Sun is in this stage now.

But, sooner or later, all the stellar supply of hydrogen must be finally exhausted. The massive and luminous stars arrive first at this critical point in evolution, and begin to contract, setting free their gravitational energy. In many

cases such contraction leads to general instability of the stellar bodies, and they burst, in brilliant explosions, into several smaller fragments. Two billion years after the "creative process" began, we find many of these hydrogen-depleted stellar fragments; they possess extremely high densities and very low luminosities and are known as "white dwarfs."

But our Sun, which uses its hydrogen supply very sparingly, is still going strong and plans to live ten times longer than it has already. It is, however, gradually becoming hotter and hotter, and threatens to burn up everything on the surface of the earth several billion years hence, before it has passed through the maximum stage of its luminosity and has begun to contract.

While the old and spendthrift stars die, a number of new stars are being formed from the gaseous material left over after the original process of stellar creation. But as time passes, most of the stars belonging to the innumerable stellar islands grow older and older.

And the year 12,000,000,000 after the Creation of the Universe, or A.D. 10,000,000,000, will find infinite space sparsely filled with still receding stellar islands populated by dead or dying stars.

Chronology

of the most important steps in the solution of problems concerning the constitution, energy production, and evolution of stars.

1.	Contraction hypothesis (Helmholtz)	1854
2.	Discovery of radioactivity (Becquerel)	1896
3.	Classification of stars into three fundamental groups (Russell)	1913
4.	The theory of stellar interiors (Eddington)	1917 *et seq.*
5.	Artificial transformation of elements (Rutherford)	1919
6.	White dwarfs as collapsed stars (Fowler)	1926
7.	The quantum theory of nuclear transformations (Gamow; Gurney and Condon)	1928
8.	Thermonuclear reactions as the sources of stellar energy (Atkinson and Houtermans)	1929
9.	Cyclic nuclear reactions in stars (Weizsäcker)	1937
10.	Evolution of stars with thermonuclear energy production (Gamow)	1938
11.	Carbon-nitrogen cycle in the Sun (Bethe; Weizsäcker)	1938
12.	The reactions of light elements in red giants (Gamow and Teller)	1939

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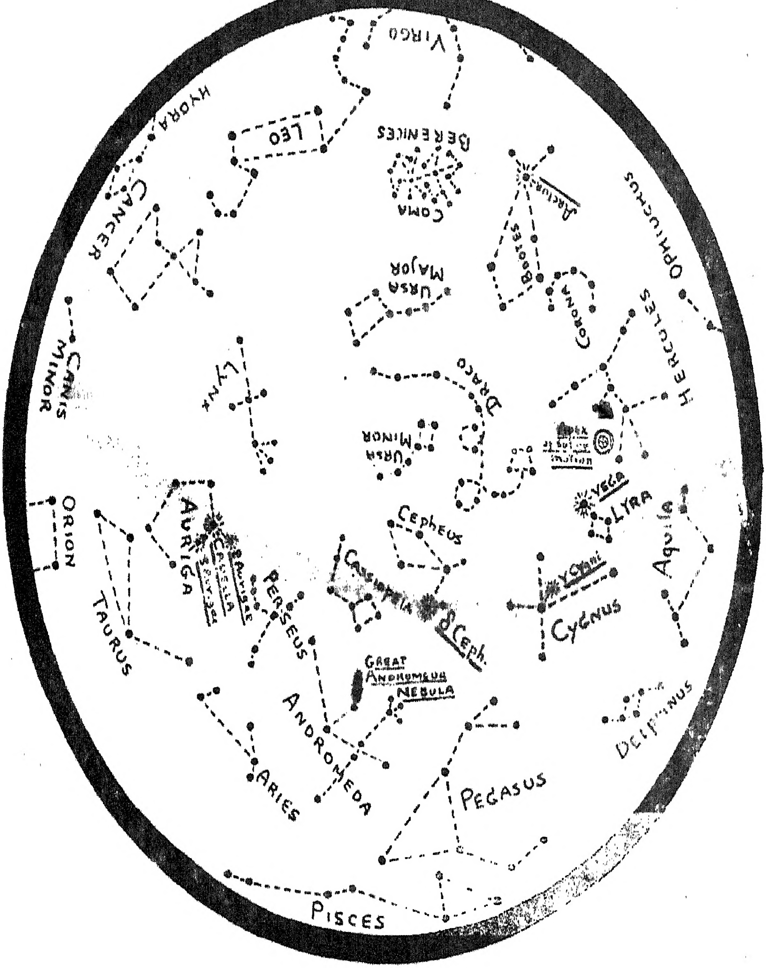

NORTHERN HEMISPHERE